제39회 첨단구조재료 심포지엄

초 록 집

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분과위원장 인사말

대한금속재료학회 회원 여러분, 안녕하십니까?

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이에 대한금속·재료학회 재료강도분과는 구조재료 분야의 최신 기술과 연구 성과를 공유하고 토론하는 자리로서 매년 '첨단구조재료 심포지엄'을 개최해 오고 있으며, 올해도 그 전통을 이어가고자 합니다.

특히 이번 심포지엄은 대한금속×재료학회 학회장을 역임하신 김성준 교수님의 정년퇴임을 기념하는 특별 강연이 함께 마련되어 있어 더욱 뜻깊은 시간이 될 것입니다. 또한, 구조재료 분야에서 활발한 연구를 이어오고 계신 여러 회원님들께서 60여 편의 수준 높은 논문을 발표해 주실 예정으로 기술적 깊이와 학문적 영감을 더하는 시간이 되리라 기대합니다.

오랜만에 서울에서 개최되는 이번 심포지엄은 학문적 교류뿐만 아니라 따뜻한 소통과 친목의 장이 되리라 기대합니다. 아울러 매년 꾸준한 성원과 후원을 보내주시는 후원사 여러분께도 깊은 감사의 말씀을 전합니다.

회원 여러분의 건강과 연구의 지속적인 발전을 기원드리며, 앞으로도 재료강도분과는 우리나라 소재산업의 지속적 발전을 위하여 최선을 다하겠습니다.

2025년 8월
(사) 대한금속•재료학회 재료강도분과위원장
어 광 준

목 차

제 39 회 첨단구조재료 심포지엄

8월 28일 [목]

제 1 발표회장

- Session 1
- Session 2

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1.5GPa급 마르텐사이트강 용접금속의 마이크로 인장물성과 수소취화 민감도

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Micro-Tensile Properties and Hydrogen Embrittlement Sensitivity of 1.5GPa-Grade Martensitic Steel Weld Metal

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ABSTRACT

최근 자동차 산업에서는 안전성 향상과 경량화를 위해 고강도 마르텐사이트 강재의 적용이 꾸준히 증가하고 있으며, 프런트 및 리어 범퍼 빔, 도어 빔, 사이드 멤버 보강재, 루프 빔 등 다양한 부품에 활용되고 있다. 마르텐사이트 강재의 용접부는 모재와는 다른 미세조직과 기계적 특성을 나타내며, 본 연구에서는 마르텐사이트 강재 용접부의 특성 및 최적 합금 조성 설계의 필요성을 제기한다. 초고강도 마르텐사이트 강재 용접부의 미세조직 설계를 통해 수소 이온의 트래핑 사이트(trapping site)를 고려한 수소취화 저항성 향상 방안을 모색하였다. 또한, 마르텐사이트 강재 용접금속의 합금 조성 및 미세조직 설계를 통해 강도 및 연성 개선 방안도 함께 검토하였다. 실험 결과, Nb가 중간 수준으로 첨가된 용접금속은 높은 함량의 Ni가 첨가된 용접금속에 비해 연성 저하가 적었다. 이는 미세 MX 입자가 비가역적 수소 트래핑 사이트로 작용한 결과로 보인다. 반면, Ti가 상대적으로 다량 첨가된 용접금속은 크기가 큰 산화물이 형성되어 수소취성 저항성이 상대적으로 낮아진 것으로 판단된다. 결정립이 미세화되고 상대적으로 미세한 MX 석출물이 형성될 경우, 용접금속의 강도가 증가할 뿐만 아니라 수소취성에 대한 저항성도 향상되었다. 반면, 산화물의 양이 증가하면 수소취성 저항성이 저하되어 용접부가 수소에 더욱 취약해지는 것이 확인되었다. 침상 페라이트가 더 많이 형성되는 경우에는 용접금속의 강도

가 상대적으로 감소하는 경향을 보였다. 또한 잔류 오스테나이트의 분율이 증가하면 수소 취성에 대한 저항성이 높아졌다. 합금 원소 조성에 따라, 기존의 높은 함량의 Ni가 첨가된 용접금속 대비, Ni를 미첨가한 상태에서 Ti를 첨가하면 산화물과 침상 페라이트가 증가하였고, Nb가 중간 수준으로 첨가된 경우 미세 MX 석출과 잔류 오스테나이트가 적정 수준으로 유지되었다. Nb가 상대적으로 높은 함량으로 첨가된 경우에는 결정립이 더 미세화되며, MX 석출과 잔류 오스테나이트도 증가하였다. 결론적으로, Ti가 상대적으로 적게 첨가되고 Nb가 중간 수준으로 첨가된 용접금속이 미세 MX 석출, 상대적으로 다량의 잔류 오스테나이트 및 소량의 산화물 형성으로 인해 경제성을 가지면서 우수한 인장 특성과 수소취화 저항성의 최적 조합을 나타냈다.

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템퍼드 마르텐사이트강의 수소취성에 미치는 Nb 및 Ti 첨가의 영향

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Effect of Nb and Ti content on Hydrogen Embrittlement of Tempered Martensitic Steel

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ABSTRACT

Tempered martensitic steels are widely used as materials for high-pressure hydrogen storage and transportation. However, their susceptibility to hydrogen embrittlement is significantly influenced by microstructural factors. This study investigates the effect of Nb and Ti addition on the hydrogen embrittlement resistance of tempered martensitic steels. By systematically varying the Nb and Ti content, the evolution of MC-type carbides was characterized using SEM, TEM, and compositional analyses.

Phase calculations show how Nb and Ti contents affect MC carbide volume fraction and temperature dependence, while compositional analyses highlight the evolution of constituent elements such as Nb, Ti, Cr, and C in these carbides (Fig. 1). The microstructural analysis results reveal that increasing Ti content promotes the formation of (Nb,Ti)C carbides, accompanied by changes in elemental partitioning (Fig. 2). These microstructural modifications enhance the density of irreversible hydrogen trap sites, thereby improving the resistance to hydrogen-induced fracture.

Mechanical testing under electrochemical hydrogen environment confirm a clear improvement in hydrogen embrittlement resistance with increasing Nb and Ti content, as reflected by relative notch tensile strength (RNTS) values. This study highlights the beneficial role of Nb and Ti in modifying carbide characteristics, and provides insight into alloy design strategies for tempered martensitic steels with improved hydrogen embrittlement resistance.

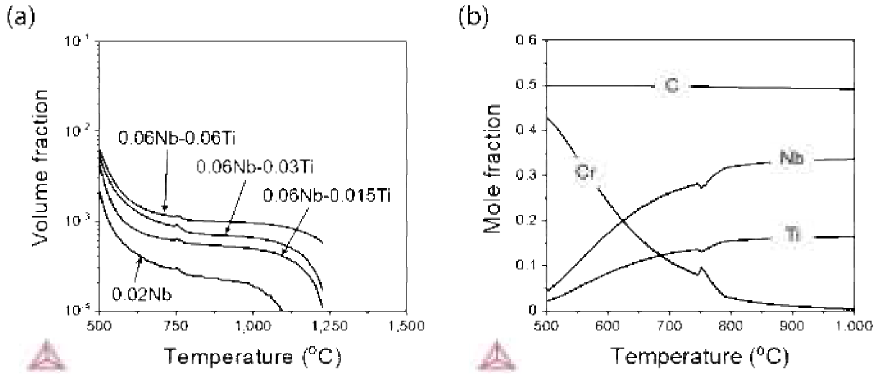

Fig. 1. (a) Variations in the volume fraction of MC carbide as a function of temperature for tempered martensitic steels with varying Ti contents. (b) Calculated atomic ratio of constituent elements in MC carbides as a function of temperature in the 0.06Nb-0.03Ti steel.

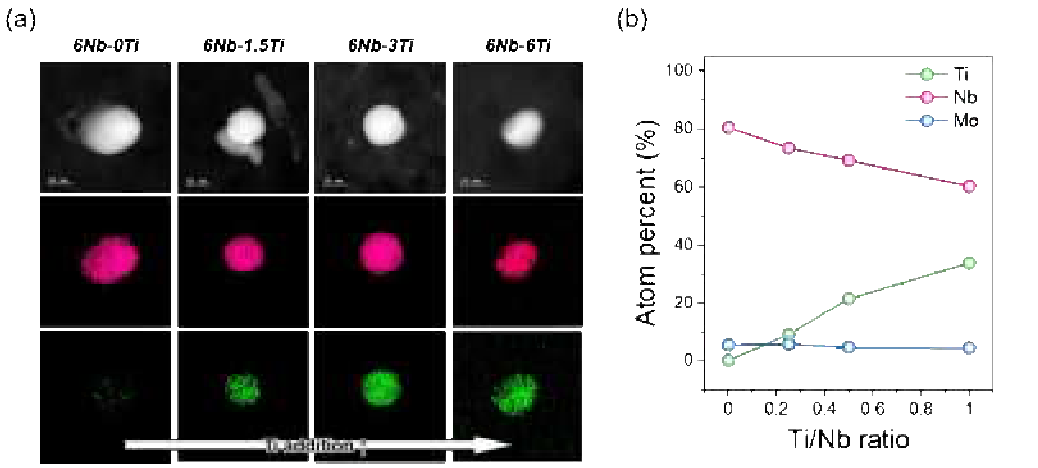

Fig. 2. (a) High-angle annular dark-field (HAADF) STEM images and EDS elemental maps showing the evolution of MC carbides in tempered martensitic steels with increasing Ti addition. (b) Atom fraction of Nb, Ti, and Mo in MC carbides as a function of Ti contents.

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페라이트 국부 변형 분산과 소성유기변형 효과 지연을 통한 초고강도 마르텐사이트 경량철강 개발

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Ultrastrong and Ductile Martensitic Low-density Steel achieved by Local Strain Partitioning into Ferrite and Delayed TRIP Effect

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ABSTRACT

The growing demand across various industries for materials that are both high in strength and lightweight has driven the development of advanced steels with exceptional strength-to-weight ratios. To date, most reported ultrahigh-strength, low-density steels have been produced through cold rolling followed by partial or complete recrystallization, with their enhanced mechanical properties primarily attributed to ultrafine-grained microstructures. This study presents an alternative strategy for designing ultrahigh-strength, hot-forged low-density steel with promising applicability in sectors such as automotive and aerospace engineering. Low-density steels with martensitic-based microstructures exhibit high mechanical strength and improved specific strength, benefiting from the density-reducing effect of aluminum

(Al). However, although Al effectively reduces material density, it also promotes the formation of coarse ferrite and broadens the intercritical (α + γ) temperature range. Consequently, efforts to increase Al content for higher weight reduction often lead to undesirable ferrite formation, thereby limiting further improvements in strength. To achieve both high strength and ductility while incorporating ferrite, a thorough understanding of how the fraction, size, and distribution of ferrite influence mechanical performance and deformation behavior, particularly through interactions among constituent phases, is essential. Accordingly, three model steels were developed through controlled annealing temperatures, producing distinct triplex microstructures consisting of ferrite, martensite, and retained austenite (RA). The contribution of each phase to strain partitioning was systematically examined using ex-situ microscopic digital image correlation (μ-DIC) and electron back-scattered diffraction (EBSD) analyses. The results demonstrate that the martensitic matrix ensures an ultrahigh strength level (1758 MPa), while a moderate fraction (~17 %) and homogeneous distribution of intercritical-ferrite (IC-ferrite) promote sustained strain hardening. The preferential strain partitioning into IC-ferrite alleviates local strains within the martensite phase, thereby preventing early exhaustion of the transformation-induced plasticity (TRIP) effect and facilitating ductile fracture behavior. This approach effectively capitalizes on the presence of ferrite, offering advantages for applications demanding both ultrahigh strength and ductility.

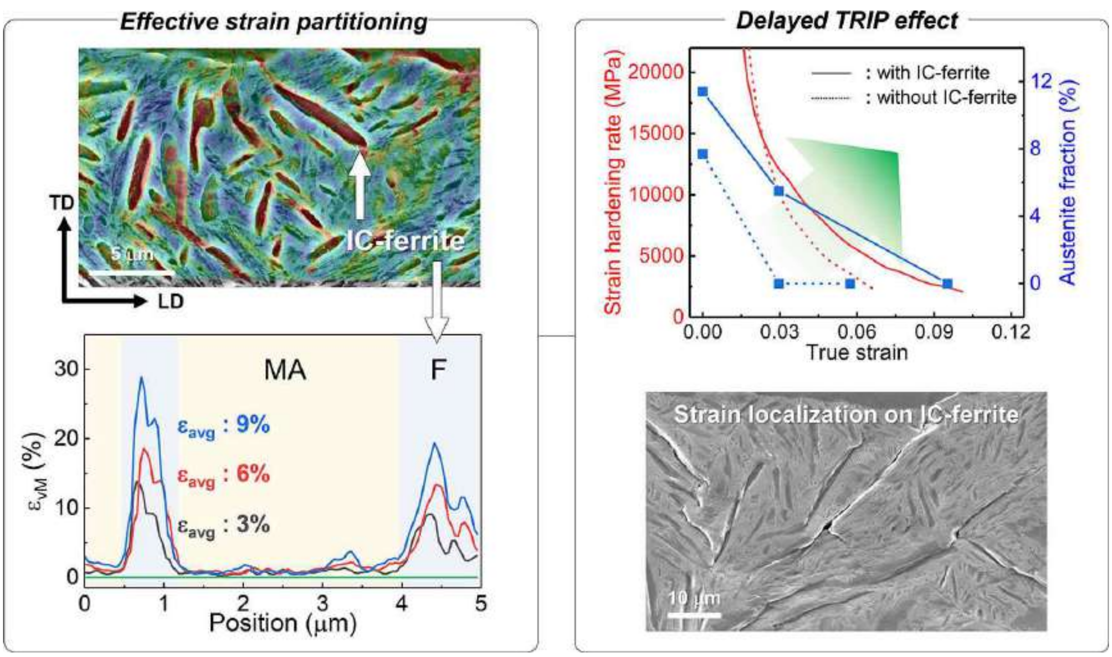

Fig. 1. (Left image) Preferential strain partitioning into IC-ferrite observed using μ-DIC analysis. (Right image) Delayed TRIP effect of RA within the martensitic matrix enhancing strain-hardening behavior.

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열처리 조건에 따른 고실리콘 강판의 집합조직 특성 변화

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Influence of annealing conditions on the crystallographic texture of high-Si steel

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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, including hot/cold rolling, tend to develop dominant γ-fiber ((111)//ND) and α-fiber ((110)//RD) textures, which are detrimental to the magnetic property. 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. In particular, we examine the effects of heating rate and annealing temperature on recrystallization behavior and texture development in High-Si steel. Electron backscatter diffraction (EBSD) analysis is conducted to elucidate the key factors governing γ-fiber suppression and cube texture enhancement.

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확산접합 Ti 판재의 접합 강도 평가

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Evaluation of the Bonding Strength of Diffusion-Bonded Ti sheets

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ABSTRACT

In this study, we proposed an integrated process between hot forming and diffusion bonding to simultaneously form and join two independent titanium alloy sheets. This process was named the Integrated Hot Forming/Diffusion Bonding (HF/DB) process. The application of the HF/DB process was anticipated to minimize the Buy-to-Fly (BTF) ratio. Initially, we estimated and analyzed the bonding characteristics of titanium alloy sheets using the HF/DB process on a lab scale. The quality of the bonded products was investigated using microstructural analysis with an optical microscope (OM) and a scanning electron microscope (SEM) equipped with electron backscatter diffraction (EBSD). A lap shear tests were conducted to evaluate the shear strength of the bonded specimens. Using the process parameters obtained from the lab-scale HF/DB process, prototypes of actual thermal shield components were manufactured. Consequently, the feasibility of the combined process of bending forming followed by diffusion bonding for Ti-6Al-4V alloy sheets was successfully demonstrated.

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레이져처리 헤테로구조화를 통한 합금의 강도, 연성, 성형성 향상

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Laser Heterostructuring of Alloys Using Laser-treated Alloys for High Strength, Ductility, and Formability

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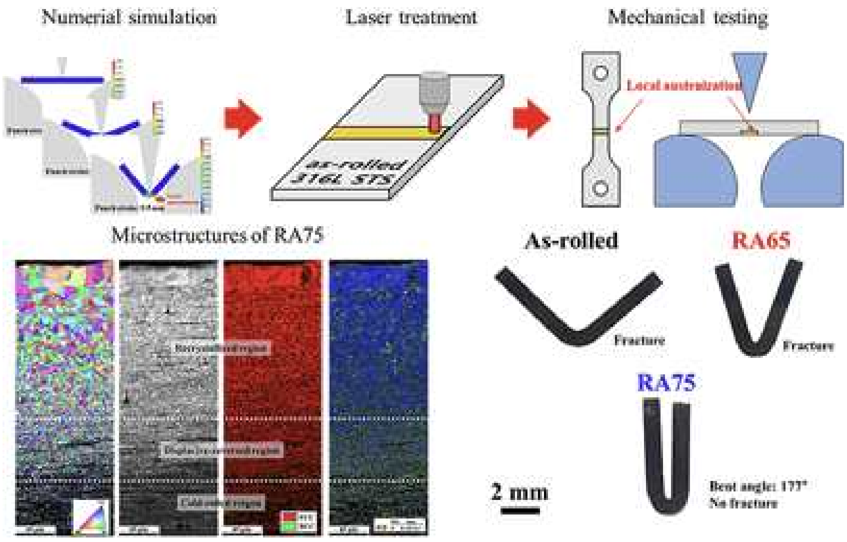
ABSTRACT

High-strength materials are crucial for structural applications, yet their often-limited formability hinders wider industrial adoption. This study introduces a novel surface heterostructuring approach using laser treatment to overcome this trade-off and achieve an exceptional balance of formability and strength in as-rolled martensitic stainless steel. By inducing localized austenitization, the laser treatment significantly enhances bendability, allowing for near 180° folding while preserving high tensile strength. This tailored microstructure, created specifically for forming through surface heterostructuring, effectively expands the current formability-strength paradigm, opening up new possibilities for material design and application.



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Zn 도금 강판의 열처리에 따른 계면 Si-enrichment 기구와 Fe-Zn 합금화 억제 현상

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Mechanism of interfacial Si enrichment and suppression of Fe-Zn alloying during annealing of Zn-coted steels

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ABSTRACT

In response to growing concerns over environmental pollution and stringent CO_2 emission regulations, reducing vehicle weight to improve fuel efficiency has become increasingly important. Accordingly, 3rd generation advanced high-strength steels (AHSS 3. Gen.) have been developed to meet the demand of weight reduction and driving safety. Retained austenite plays a key role in achieving the excellent strength-ductility combination of AHSS 3. Gen., stabilized via carbon partitioning during steel processing. Si is a key element in stabilizing retained austenite through suppression of carbide formation. However, it can cause underalloying during galvannealing and liquid metal embrittlement during welding in Zn-coated steels. This study investigated the mechanism of Si-enrichment at the interface between the steel substrate and Zn coating, as well as the resulting suppression of Fe-Zn alloying during annealing. To this end, two steels with different Si contents (0 and 2 wt%) were prepared, and both were electrogalvanized to form Zn coataing. The coated steels were then annealed at at 600 ℃ in a commercial furnace for various durations. The overall Fe-Zn alloying suppression behavior was examined using field-emission scanning electron microscopy (FE-SEM) and X-ray diffraction (XRD). In addition, the

detailed interfacial microstructural analysis was conducted using high-resolution transmission electron microscopy (HR-TEM) and atomic probe tomography (APT). Thermodynamic simulations were also performed to analyze the diffusion behavior of individual elements, as well as interface migration and phase transformation. With increasing annealing time, Zn diffusion into the steel matrix was observed in both steels. However, in the 2 wt% Si steel, Zn diffusion and the formation of the Fe-Zn alloying layer were significantly suppressed, whereas active alloying occurred in the 0 wt% Si steel (Fig. 1). A distinct Si-enrichment phenomenon at the steel/Zn interface was identified in the high-Si steel. The underlying mechanism of Si-enrichment and its role in suppression of Fe-Zn alloying are discussed in detail.

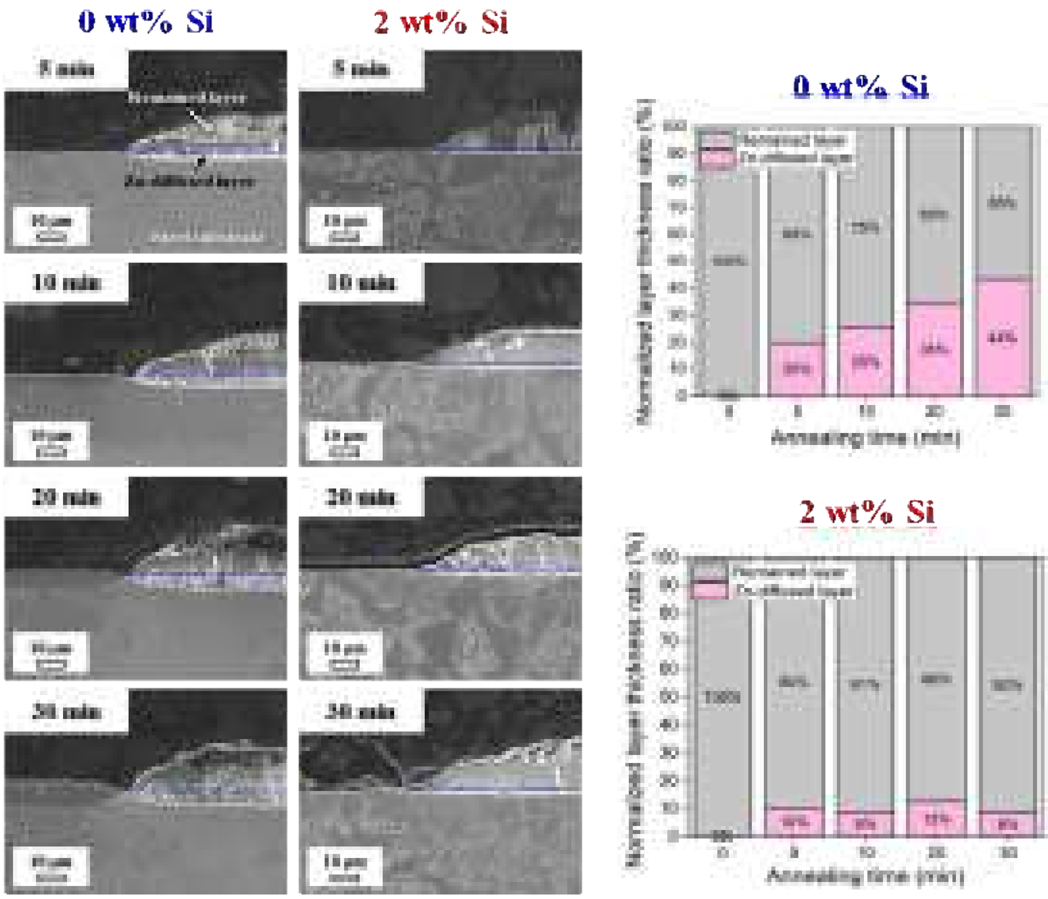

Fig. 1. Zn diffusion behavior and interface migration during annealing at 600 °C for steels with different Si contents (left), and normalized thickness ratio of the Fe-Zn reaction layer as a function of annealing time (right)

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고내식 경량고강도 상변태 거동 해석

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Phase transformation behavior in corrosion resistant FeMnAlC Lightweight Steel

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ABSTRACT

The phase transformation behavior of a lightweight steel with the composition Fe-29.1Mn-12.5Al-1.35C-4.95Cr was investigated in this study. This steel was developed based on a Cr-containing Fe-Mn-Al-C alloy system, proposed as a new class of lightweight stainless steels. It exhibits a favorable combination of high specific strength and ductility, along with corrosion resistance comparable to conventional stainless steels [1]. The microstructure consists of austenite, ferrite, and κ-carbide, the latter contributing to precipitation strengthening. While Cr is generally known to suppress κ-carbide formation, this effect was negligible in the present study due to the high Al and C contents, which promote κ-carbide precipitation. Thermodynamic calculations using Thermo-Calc (TCFE12 database) indicate that κ-carbide begins to form below 1000 °C, as shown in Figs. 1(a) and 1(b), suggesting that κ-carbide can precipitate even under rapid cooling conditions. In the temperature range of 550 - 850 °C, FeAl-type B2 phase, κ-carbide, and carbides such as $M_{23}C_6$ and M_7C_3 are expected to form. However, the undesirable β-Mn phase was observed

to nucleate at grain boundaries during the early stages of heat treatment and subsequently grow into the interior of austenite grains. According to the phase diagram in Fig. 1(b), β-Mn forms when the carbon content drops below 5 wt.%. It is presumed that the precipitation of intergranular carbides ($M_{23}C_6$ or M_7C_3) locally consumed carbon near the grain boundaries, leading to carbon-depleted zones that facilitated β-Mn formation. Additionally, β-Mn formation and growth proceeded more rapidly at elevated temperatures, exhibiting temperature-dependent morphological variations. This study focuses on understanding the mechanisms behind the unwanted precipitation of β-Mn and its impact on the phase transformation behavior.

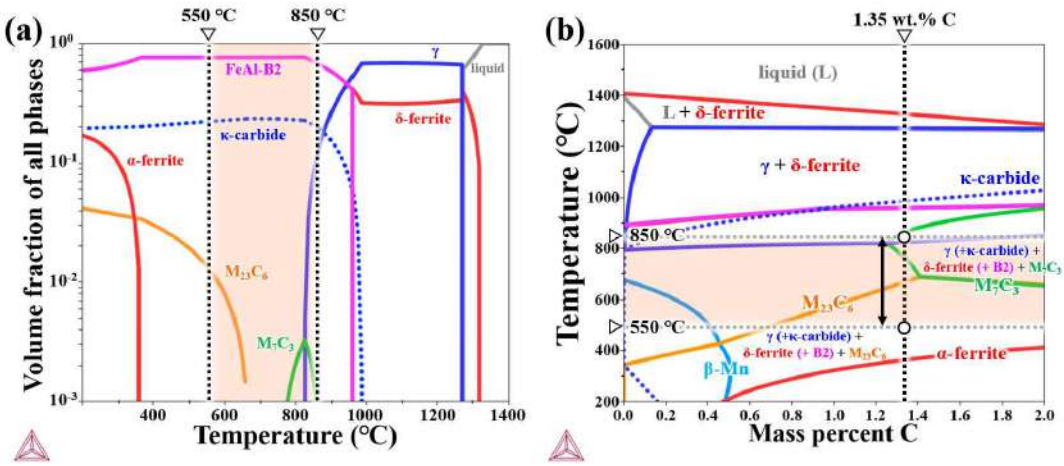

Fig. 1. Phase diagram calulcated using Thermo-Calc software (TCFE12 ver.): (a) phase fraction vs temperature, and (b) temperature vs C wt.% diagrams.

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항복 강도 1 GPa 이상급 초고장력 강판의 결정 소성 유한 요소 해석 적용 사례

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Application of Crystal Plasticity Finite Element Model to Advanced High Strength Steels with Yield Strengths Above 1 GPa

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ABSTRACT

Advanced high-strength steels (AHSS) are extensively used in automotive structures to meet requirements for high strength and lightweighting. Often AHSSs exhibit releatively limited formability and pronounced springback, posing challenges in subsequent metal forming and springback predictions. Moreover, certain AHSSs with martensitic phase exhibit a pronounced tension-compression asymmetry, which conventional Schmid law emplyed in the crystal plasticity cannot accurately capture.

In this study, the ΔEVPSC (stress increment-based elasto-visco-plastic self-consistent) model [1,2] was used to simulate the mechanical behavior of two AHSSs, DP980 and MART1500Y. Building upon the work of Jeon et al. [3], who applied the ΔEVPSC model to U-draw bending and springback of DP980, the present study expands its use to simulate the springback behavior of a more complex C-rail channel die draw. This geometry induces significant position-dependent strain path changes, allowing for a more rigorous validation of the model. Additionally, a simplified non-Schmid formulation was introduced to capture the tension-compression asymmetry observed in MART1500Y, both qualitatively and quantitatively.

DP980, with a dual-phase microstructure of ferrite and martensite, was modeled

using grain orientation distribution from EBSD measurements. Material parameters were calibrated using various mechanical tests, including uniaxial tension, compression, cyclic loading, and bulge tests. Springback profiles from both U-draw and C-rail simulations were evaluated using the ΔEVPSC-FE model [2] and showed good agreement with experimental measurements.

MART1500Y, a fully martensitic steel with a yield strength of around 1.5 GPa, exhibits a flow stress difference of approximately 3.4% between tension and compression. To model this, a simplified non-Schmid effect was introduced into the slip activation criterion for BCC structures. Despite its simplicity, the model successfully reproduced the experimentally observed asymmetry and demonstrated comparable accuracy to more complex approaches.

This work demonstrates that the ΔEVPSC model can be extended to capture both forming behavior and asymmetric mechanical responses in AHSS. The simplified non-Schmid formulation was sufficient to describe the asymmetry in martensitic steels. Future studies will focus on integrating this non-Schmid framework into the finite element interface of ΔEVPSC model via user material subroutine (UMAT)[2] and applying it to complex forming simulations under varying strain paths and loading conditions.

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지진 후 화재 환경에서 석출물-클러스터 복합 강화가 적용된 베이나이트강의 피로 변형 거동 고찰

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Fatigue Deformation Behavior of Precipitate-Cluster-Strengthened Bainitic Steel under Post-Earthquake Fire Scenarios

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ABSTRACT

With the increasing construction of high-rise and multi-purpose buildings, stricter structural safety requirements have been enforced to ensure resistance against both earthquakes and fires. Among structural steels, H-section steels are commonly used as core columns and beams in high-rise buildings, where they must withstand seismic impact and remain structurally stable even in post-earthquake fires to prevent large-scale human and economic losses. Therefore, these steels must simultaneously meet the criteria for seismic resistance—such as a low yield ratio ($\leq$ 0.8)—and fire resistance, which demands the retention of at least two-thirds of the yield strength at 600 °C. However, improving one property often compromises the other. For example, increasing solute atom content enhances fire resistance through precipitation strengthening but may elevate the yield ratio, making it less favorable for seismic applications. This trade-off has made it challenging to develop structural steels suitable for post-earthquake fire (PEF) conditions. In response, bainitic microstructures have been widely explored due to their potential to deliver both strength and thermal stability [1]. Microalloying elements such as Mo, V, Ti, and Nb have been proposed to enhance high-temperature strength through controlled

precipitation [2]. Nevertheless, few studies have comprehensively addressed fatigue behavior under combined seismic and thermal loading, which is critical for structural integrity in actual PEF scenarios. In this study, a low-carbon bainitic H-section steel, microalloyed with Mo, V, Ti, and Nb, was developed to meet the demands for both seismic and fire resistance applications. The steel exhibited an impressive yield ratio (< 0.8) and maintained over two-thirds of its yield strength at 600 °C, fulfilling dual performance criteria. To evaluate its structural integrity under a post-earthquake fire (PEF) scenario, a complex low-cycle fatigue (LCF) protocol was employed: room-temperature LCF tests were first conducted up to 10 cycles to simulate seismic loading, followed by thermal exposure at 600 °C for 2 hours to mimic post-earthquake fire, and finally resumed LCF testing until failure. As shown in Fig. 1, the initial microstructure consists primarily of bainite with dispersed MX precipitates and solute clusters. Notably, the complex LCF condition exhibited enhanced strength after thermal exposure and achieved superior fatigue life compared to single-step LCF. To gain deeper insights into the fatigue behavior under complex loading, detailed microstructural analysis was conducted using TEM and 3D atom probe tomography (APT). These analyses revealed that the combined effects of fine MX precipitation and solute clustering contributed to dislocation pinning and suppressed cyclic softening. These findings will be incorporated into the discussion to provide a profound understanding of the complex behaviors under fatigue and thermal exposure.

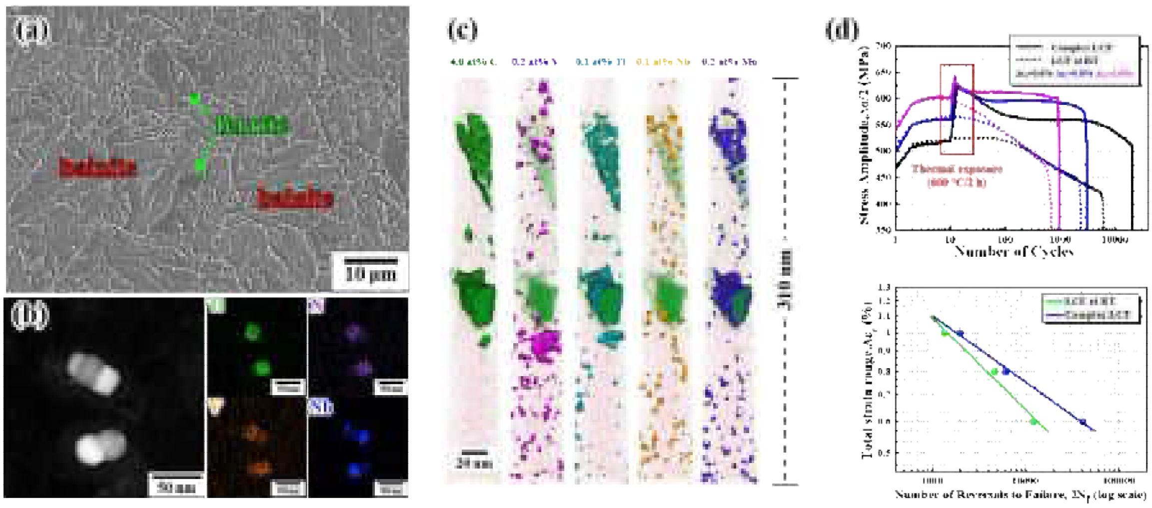

Fig. 1. Initial microstructure and fatigue properties of Fire- and seismic-resistant low carbon steel: (a) SEM image showing bainite and ferrite phase, (b) STEM-EDS of fine MX precipitates, (c) 3D-APT reconstruction showing (C,Nb,Mo,V,Ti) solute clusters (d) cyclic stress response graph and coffin manson plots under single and complex low-cycle fatigue condition.

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- Session 2

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계장화 압입시험(IIT) 기반 AI 연계 신뢰성 예측 및 유지관리 체계 개발 전략

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Development Strategy for AI-Integrated Reliability Prediction and Maintenance System Based on Instrumented Indentation Testing (IIT)

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ABSTRACT

산업 인프라의 고도화에 따라 구조물과 부품의 장기 신뢰성 확보는 핵심 과제로 부상하고 있다. 본 발표에서는 계장화 압입시험(Instrumented Indentation Testing, IIT)을 활용해 현장에서 직접 획득한 물성 데이터를 기반으로, 인공지능(AI) 분석 기법을 접목한 신뢰성 예측 및 수명관리 체계 구축의 새로운 방향을 제시한다. IIT는 탄성계수, 강도, 파괴인성, 접착력, 잔류응력 등 다양한 기계적 특성을 비파괴적으로 정량화할 수 있어, 실제 운용 환경에서의 열화 상태를 정밀하게 반영할 수 있는 강점을 지닌다. 이러한 정량 데이터는 압입곡선 정보와 함께 기존 수명예측 모델의 입력 변수로 활용되거나, AI 기반 예측 모델 학습을 위한 핵심 데이터로 적용되어 신뢰성 기반 평가 체계 정립에 기여할 수 있다. 본 발표는 IIT 기반 물성 정보와 AI 분석을 융합한 하이브리드 수명관리 체계의 개발 취지를 공유하며, 기존의 파괴 시험 및 이론 기반 모델이 가지는 한계를 보완할 수 있는 새로운 기술적 대안을 제시하고자 한다. 이러한 접근은 취약부 검증, 구조물 유지보수 전략 수립 등 다양한 단계에 적용 가능하며, 소재 및 공정의 품질 관리, 신뢰성 평가 등 차세대 제조 기술로도 효과적으로 확장될 수 있다. 향후 산학연 협업 체계를 통해 물성 DB, AI 모델, 예측 알고리즘, 현장 적용 시스템을 통합적으로 구축한다면, 원전 관리 및 해체, 수소 배관, 항공우주, 플랜트는 물론 전자부품 및 적층제조(3D 프린팅) 분야의 미세 스케일까지 아우르는 국제 경쟁력 있는 신뢰성 기반 수명관리 플랫폼으로 발전할 수 있을 것으로 기대된다. 나아가, 본 체계는 기술 검증 및 산업 인증은 물론, 관련 국제 표준화 추진의 기반 기술로도 발전 가능성이 높다.

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Global and Local Deformation Behavior of Additively Manufactured Multi-Layered Medium-Entropy Alloys

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ABSTRACT

This study investigated the micromechanical behavior of additively manufactured multi-layered samples consisting of alternating layers of hard CoCrNi and soft $CoCrNi_2$ medium-entropy alloys (MEAs), subsets of the Cantor high-entropy alloy. The multi-layered MEAs were fabricated via laser powder bed fusion (L-PBF). Global and local deformation behaviors were examined using macro- and micro-scale digital image correlation (DIC) techniques, respectively. The findings highlighted the intricate interplay between local and global deformation, which was discussed in terms of the constraint of plastic deformation within each layer and interfacial region, and its underlying mechanisms. This relationship was further explored through nanoindentation experiments conducted on each layer before and after hydrogen charging, providing comprehensive insights into how hydrogen modulates the deformation behavior in the multi-layered MEA system.

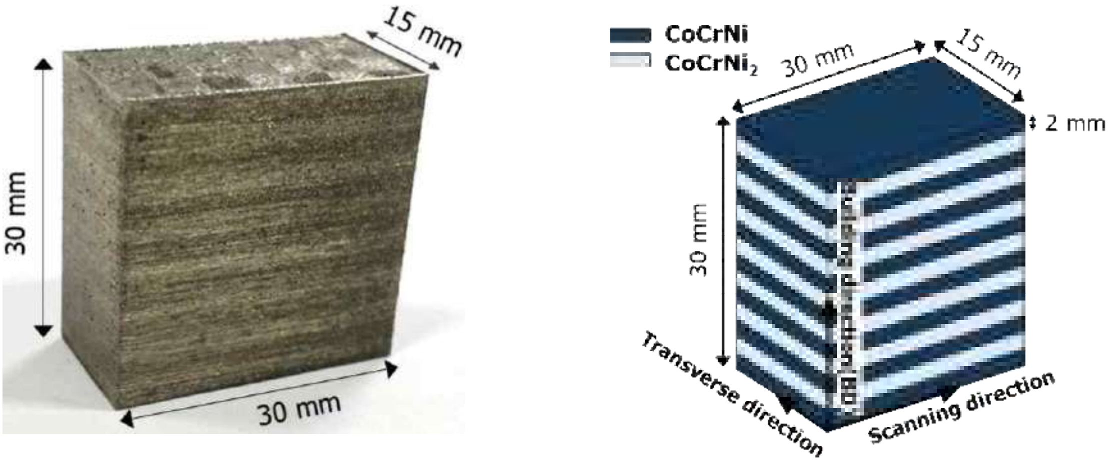

Figure 1. Sample photo and schematic illustration of the examined multi-layered MEA.

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기계적 모델링을 활용한 대면적 전개형 최소침습 소자 설계

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Structural Design of Minimally Invasive Devices
with Large-Area Deployment Using Mechanical Modeling

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ABSTRACT

As human life expectancy continues to increase, there is a rapidly growing demand for advanced bio-health monitoring technologies that enable early diagnosis and personalized treatment through the precise measurement of physiological signals. Since most of these signals originate from deep tissues within the body, it is difficult to acquire high-fidelity information solely from the skin surface. To address this, implantable sensors that can be placed in close proximity to the signal source—such as the heart, brain, spinal cord, and muscles—are essential for accurate and continuous monitoring. Minimally invasive surgical approaches have gained attention as a means to reduce surgical trauma while enabling effective sensor implantation. However, the physical constraints of the insertion route limit the allowable size of the device, creating an inherent trade-off between miniaturization for insertion and a large-area coverage for signal acquisition. To overcome this limitation, we propose a

novel implantable device composed of a biodegradable shape memory polymer that can be compactly packaged within a narrow syringe prior to insertion and then autonomously unfold into a large-area configuration in response to body temperature after implantation, as depicted in Figure 1. The device is designed to sense neural signals over a wide area and naturally degrade after its functional lifetime, eliminating the need for surgical retrieval. Furthermore, finite element-based mechanical modeling is employed to quantitatively analyze the internal stress and strain induced during the high-deformation deployment process. This analysis guides the structural optimization of the device to ensure reliable mechanical performance under extreme deformation conditions. Through this approach, we aim to establish a programmable, mechanically robust platform that simultaneously achieves ultra-compact packaging and large-area

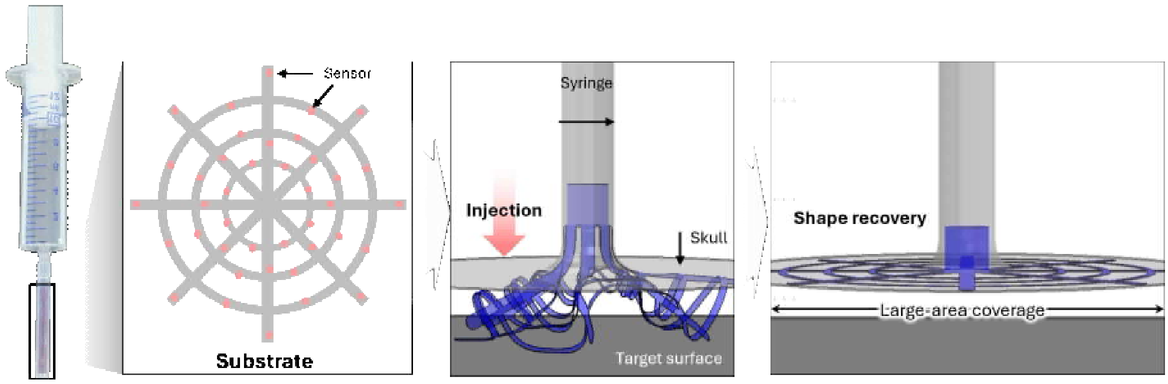

Figure 1 Schematic illustration of a large-area coverage device packaged into a small-diameter syringe and its deployment process through a narrow gap via shape recovery.

sensing—representing a new paradigm in implantable bioelectronic systems.

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무방향성 Fe-Si계 합금의 최종 열처리 분위기와 자성 특성의 상관관계 분석

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Correlation between atmospheric condition of final annealing and magnetic properties of non-oriented Fe-Si alloys

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ABSTRACT

Fe-Si alloys shows high permeability and magnetic flux density due to its crystal structure and stability of ferrite phase from high silicon content. Therefore, Fe-Si alloys are crucial materials used in electric motors, where they function to convert electrical energy into magnetic and kinetic energy. Main challenge in improving electric motor performance is reducing energy loss that occurs during the conversion of electromagnetic energy into motion. The energy loss in electric motors is called core loss, which is significantly influenced by microstructural characterisitcs of materials. In particular, microstructural characterisitcs like grain size, distribution of inclusions, texture, thickness of surface film are determined by final annealing in manufacturing process. For designing easily magnetized materials, optimal conditions of manufacturing process like annealing temperature, time have been extensively studied. However, effect of atmospheric condition of final annealing is not fully investigated. To improve the performance of electric motors, we investigate the correlation between atmospheric condition of final annealing and core loss by analyzing the mechanism to change microstructural characterisitcs by annealing

atmosphere.

In this study, change of core loss was investigated depending on atmospheric condition, controlling the percentage of hydrogen and nitrogen gas in the annealing chamber. Single sheet tester was used for measuring core loss, dimension of sample is 60 mm x 60 mm. Morphology of inclusions, grain size and surface characteristics are investigated by SEM, TEM, EDS, XPS, EBSD. Notably, the distribution of inclusions, which significantly affects core loss, was quantitatively analyzed using EDS as illustrated by figure 1. This work seeks to clarify the primary material property factors responsible for core loss.

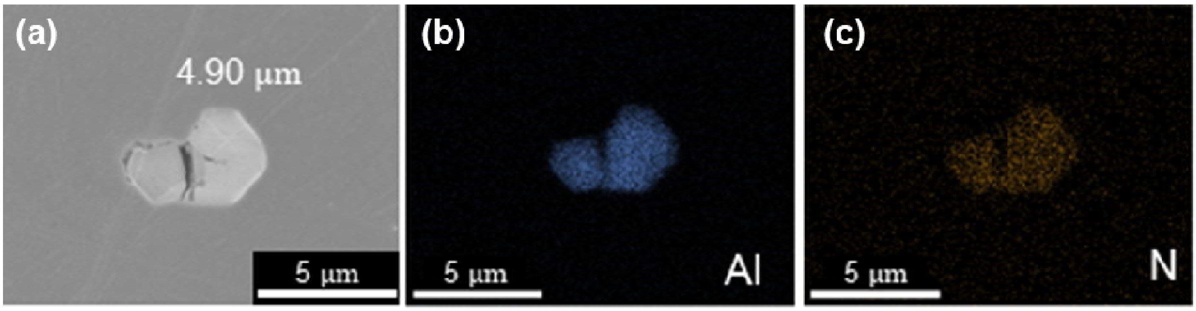

Figure 1. SEM micrograph of inclusions and EDS mapping analysis: (a) secondary electron image of SEM and (b) Al(blue), (c) N(orange) elemental mapping using EDS.

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대면적 나노격자 패널 기반 근우주 비행체

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Near-space Levitation Device based on Large Nanolattice Panel

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ABSTRACT

Nanolattices have emerged as promising ultralight materials with exceptional mechanical and thermal properties. However, conventional nanolattice fabrication has relied heavily on multi-photon lithography, which is inherently slow, costly, and limited in scalability due to its serial writing nature. These constraints have restricted the application of nanolattice-based devices to microscale dimensions and laboratory settings.

In this work, we overcome these limitations by introducing a novel, fast, and scalable fabrication process for ultralight nanolattice panels – termed nanocardboard – using photolithography, deep reactive ion etching (DRIE), atomic layer deposition (ALD), and XeF_2 gas etching. Our process enables the formation of large-area nanolattice structures entirely from thin films, with thickness around 100 nm, and densities as low as 5 – 20 kg/m^3. The resulting structures exhibit exceptional specific stiffness and thermal insulation, outperforming traditional aerogels and previously reported nanolattices.

Leveraging the unique combination of low density and low thermal conductivity, we demonstrate that these nano-cardboard panels can harness photophoretic forces to achieve light-driven levitation under sunlight intensity below 1 sun. Through finite element simulations and experimental validation, we optimized ligament geometries to

tailor buckling resistance and mechanical robustness.

Finally, we propose the use of this levitating nanolattice platform as a novel near-space flight device, particularly suitable for environments with low atmospheric density such as the stratosphere or the Martian atmosphere, where conventional rotor-based systems fail. This work opens a new pathway for scalable production of nanostructured levitation devices and expands the functional potential of ultralight materials in extreme environments.

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박막 적층동안의 미세구조 모사를 위한 시간, 길이 몬테카를로 시뮬레이션 모델 연구

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A real time-length scaled Monte Carlo simulation for the microstructural evolution during the thin film deposition

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ABSTRACT

The evolution of the microstructure during the deposition of the metallic thin film is predicted using a real time-length scaled Monte Carlo Potts model. Specifically, the diffusion coefficient of monomers is introduced in the conventional model to approximate the conversion of the simulation time and length to real measures. This model incorporates two primary dynamic mechanisms for microstructural evolution: 1) spin exchange, which mimics the diffusion of matters, and 2) spin flip, which represents the grain growth. The detailed explanation on the Potts model, including the realization of the deposition process, is presented. Using the proposed model, one can make a plausible prediction 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 to be 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, grain size becomes larger; 3) higher kinetic energy promotes more columnar grain morphology. The resultant microstructural characteristics obtained from the proposed model are also found to be analogous to the predictions from the structure zone model.

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적층제조용 고강도·고전도 알루미늄 합금의 데이터 기반 설계

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Data-driven Design of High-Strength and High-Conductivity Aluminum Alloys for Additive Manufacturing

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ABSTRACT

This study presents a data-driven approach for the design of aluminum alloys tailored for directed energy deposition (DED), a form of additive manufacturing. Targeting the simultaneous optimization of conflicting properties—namely, hardness and electrical conductivity—the research integrates experimental data with machine learning and generative modeling to predict suitable compositions and process parameters.

A dataset comprising 48 aluminum-based DED samples, including both compositional and process variables, was collected and augmented. An artificial neural network (ANN) was trained to predict processing routes for given hardness values, and the resulting synthetic data were refined using latent space filtering through a variational autoencoder (VAE). Additionally, a gradient boosting regression (GBR) model was fine-tuned via grid search and cross-validation to accurately predict electrical conductivity based on the generated inputs, completing the property set for each instance.

To assess the fidelity and diversity of the generated dataset, K-nearest neighbor (K-NN) classification and t-distributed stochastic neighbor embedding (t-SNE) visualization were employed. The generated data achieved classification accuracies above 0.7 across multiple property intervals, with F1-scores exceeding 0.75 in most ranges, indicating high similarity to experimental data. t-SNE projections further demonstrated that the synthetic data effectively captured the underlying

distribution of the experimental domain while bridging sparsely populated regions.

The proposed framework enables the generation of high-quality synthetic data from limited experimental input, offering a scalable and efficient methodology for materials design in data-constrained environments. This approach is expected to facilitate accelerated alloy development and process optimization in additive manufacturing applications.

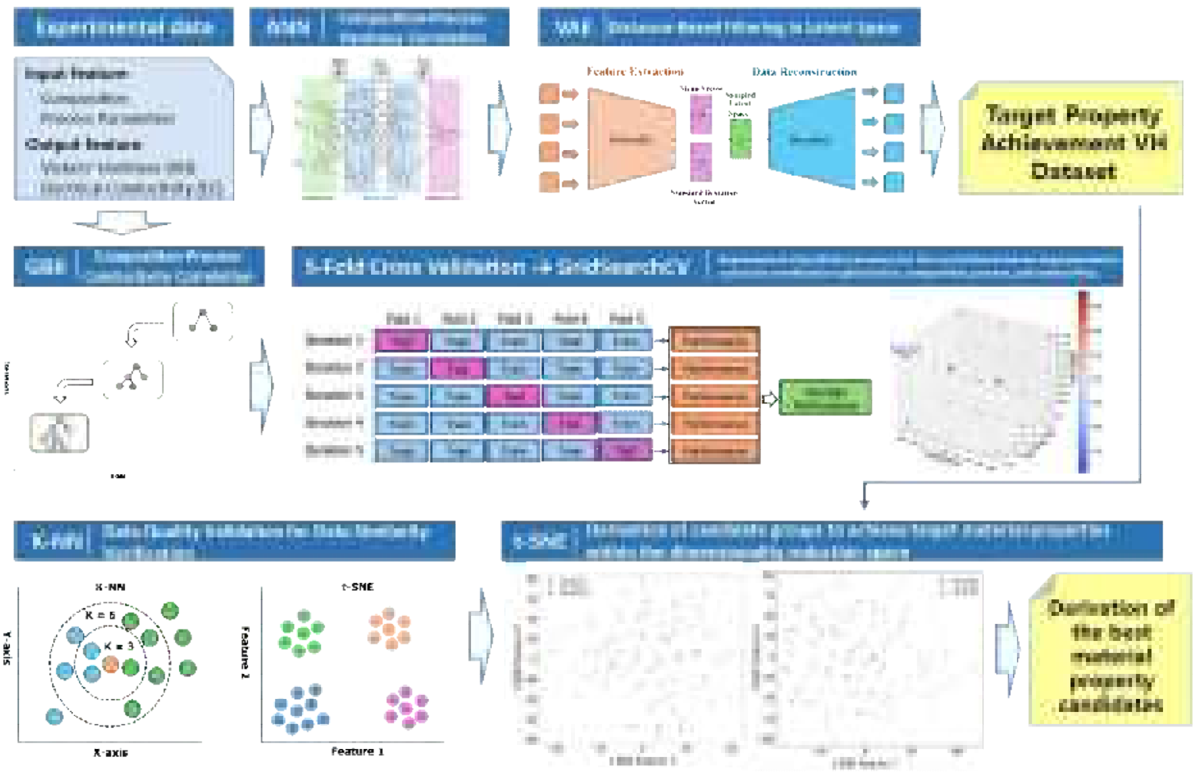

Figure 1. Machine learning and generative modeling framework for the design of aluminum alloys in DED process

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직접용융증착된 IN738LC 열처리에 따른 미세조직 및 기계적 특성 변화

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Heat treatment effect on the microstructure and mechanical properties of laser directed energy deposited IN738LC alloy

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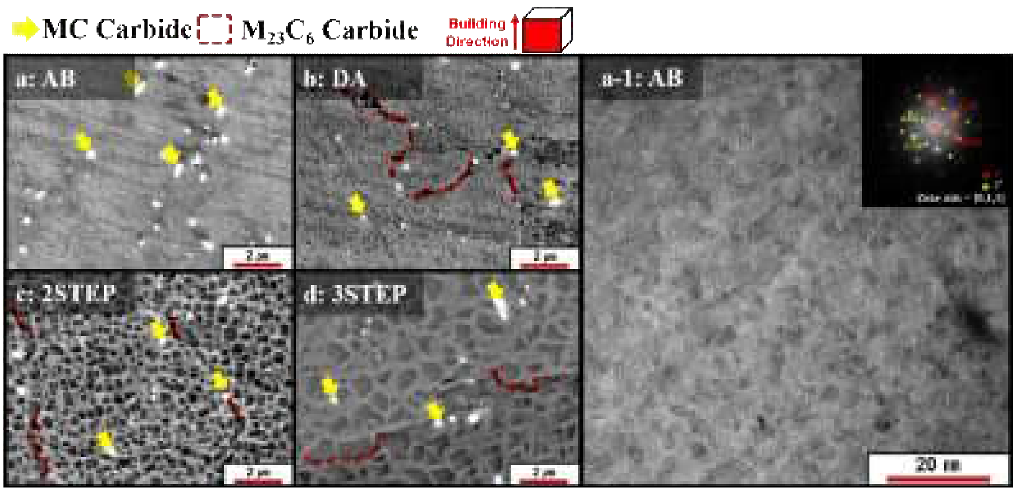
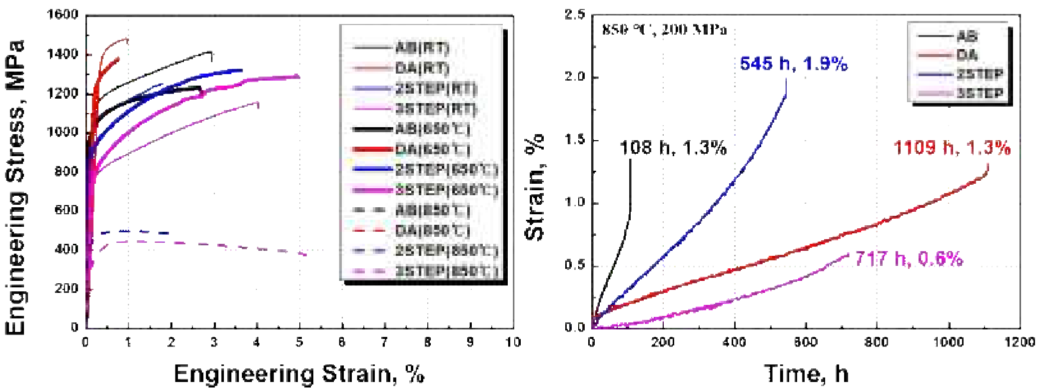
ABSTRACT



Additive manufacturing of high-grade Ni-based superalloys becomes important ussue for manufacturing and repairing of complex-shaped components for gas turbine systems. However, high crack susceptibility of high-grade Ni-based superalloys limits the processing window. To overcome this problem, in the present work, laser directed energy deposition was conducted with a low laser power and a small beam diameter.

By combing these two processing variables, heat affected zone during directed energy deposition has been reduced that results into the microcrack suppression in Inconel 738LC alloy. Also, intrinsic heat energy from repetitive laser scanning induces nanosized γ’ phase even in the as-built state that allows to achieve high strength after additive manufacturing. After conducting post-heat treatment, both γ’ phase size and channel width increased as increasing of heat treatment step. Also, aging treatment induces $M_{23}C_6$ carbides at the (Ti, Cr)-enriched segregation while additional of solution treatment reduces a $M_{23}C_6$ carbide fraction due to the segregation dissolution.



Finally, directed aged sample, which has the highest γ’ phase and $M_{23}C_6$ carbide fractions achieved the highest tensile strength and creep resistance at elevated temperature. This result shows the minimized heat input during directed energy deposition allows to get crack-free components consist with high-grade Ni-based superalloys. Also, nanosized γ’ phase and ultrafine $M_{23}C_6$ carbide in the heat treated Inconel 738LC alloy provide a positive effect to the strength and creep resistance.

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세라믹 강화 적층제조 Inconel 718 초내열합금의 고온 기계적 특성

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Enhanced High Temperature Mechanical Properties of Ceramic-Reinforced Inconel 718 Superalloy via Metal Additive Manufacturing

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ABSTRACT

Inconel 718은 650-700°C의 고온에서 우수한 기계적 특성을 보여 항공우주 및 발전용 부품에 주로 사용되는 석출 강화 니켈 기 초내열합금이다. 본 연구는 Inconel 718의 전통적 제조 공정의 한계를 극복하기 위해 레이저 분말 기반 지향성 에너지 증착(LP-DED) 기법을 활용하여 탄화 하프늄(HfC)과 질화티타늄(TiN)으로 강화된 Inconel 718 복합재의 미세구조 및 고온 기계적 특성에 미치는 영향을 탐구하였다.

Inconel 718 분말은 표면 개질 및 강화 이식(SMART) 공정을 통해 HfC 또는 TiN 입자로 균일하게 코팅되었다. LP-DED 공정 중 HfC의 도입으로 레이저 빔 흡수율은 0% HfC 샘플의 30% 수준에서 6% HfC 샘플의 약 55% 수준으로 크게 향상되었다. 이는 국부적인 가열을 유도하여 HfC의 용해와 Ni_5Hf, (Hf,Nb,Ti)C, Hf-rich Laves 상과 같은 이차상의 형성을 촉진하였다. 이러한 이차상들은 기지 상에서 Nb 고갈을 유발하면서 결정립 미세화에 기여하고 미세구조를 안정화시켰으며, γ′/γ″ 공석출을 촉진하였다. HfC 함량 증가에 따라 결정립 크기가 점진적으로 감소하고 주상정 구조가 유지되거나 등축정으로 전환되는 경향이 관찰되었다. 또한 HfC 첨가 시 전위 밀도가 0% HfC 샘플의 1.2×10^{15} m^{-2}에서 6% HfC 샘플의 2.0×10^{15} m^{-2}로 증가하였다.

TiN 강화 샘플에서는 TiN의 부분적인 분해 및 재석출이 발생하여 Ti와 N이 γ 기지로 방출되며 국부적인 화학적 조성과 상 평형을 변화시켰다. 이로 인해 3wt% TiN 샘플에서 최대 47%의 결정립 미세화가 나타났으며, γ′ 석출은 증가하고 γ″ 석출은 억제되었다. 또한 열처리를 통해 유해한 Laves 상이 효과적으로 용해되었다.

고온 기계적 시험 결과 650°C에서 HfC 강화 Inconel 718 샘플은 현저한 고온 기계적 특성 개선을 보였다. 1.5 vol% 및 3 vol% HfC로 강화된 샘플은 미강화 적층제조 샘플

대비 우수한 인장 강도와 연신율을 나타내었으며, 세레이션 거동이 관찰되지 않았다. 특히, 1.5% HfC 및 3% HfC 샘플은 항복 강도에서 각각 25% 및 22% 증가를 보였고, 연신율은 0%HfC 샘플 대비 450% 이상 향상되었다.

TiN 강화 Inconel 718 시편 또한 650°C에서 강도 개선을 보였다. 3wt% TiN 시편의 항복 강도는 1371 MPa에 도달하며 미강화 적층제조 시편(940 MPa) 대비 크게 향상되었다. 그러나 TiN 강화 시편에서 동적 변형 시효(DSA)가 강화되는 경향을 보였으며, Type-B에서 Type-C 세레이션 모드 전환 및 세레이션 진폭 증가가 관찰되었다. 2wt% TiN 샘플은 1174 MPa의 항복 강도로 미강화 샘플(항복 강도 940MPa) 대비 우수한 강도-연신율 균형을 달성하였다. TiN 강화 Inconel 718의 강도 증가는 γ'/γ'' 전단, 고용 강화, 전위 경화의 시너지 효과에 기인한다. 특히 침입형 질소는 탄성 용질-전위 상호작용을 통해 27-94 MPa의 추가적인 강도 증진에 기여하였다. TiN 첨가 시 세레이션 거동이 사라지지 않은 반면에, HfC 첨가 시에는 고온에서 세레이션 거동이 사라진 이유는 Nb, Mo, Cr과 같이 전위와 상호작용할 수 있는 용질 원자들의 편석을 용해되었다가 재석출되는 탄화물이 흡수하는 경향성에 기인한 것으로 판단된다. HfC의 경우 석출된 탄화물에서 Ti, Nb 등 기지 원소들이 함께 관찰된 반면, TiN의 경우 석출된 TiN에서 Ti 외의 용질 원자는 관찰되지 않았다.

이러한 결과는 LP-DED를 이용한 고성능 Inconel 복합재 제조 시 세라믹 강화재의 레이저 빔 흡수율 강화의 중요성과, 세라믹 강화 Inconel 718이 고온 응용 분야에서 큰 잠재력을 가지고 있음을 확인시켜 준다. 향후 장기 크리프 시험을 포함한 추가 연구가 적층제조된 세라믹 강화 Inconel 718 합금의 실용적 응용에 대한 적합성을 평가하는 데 필요하다.

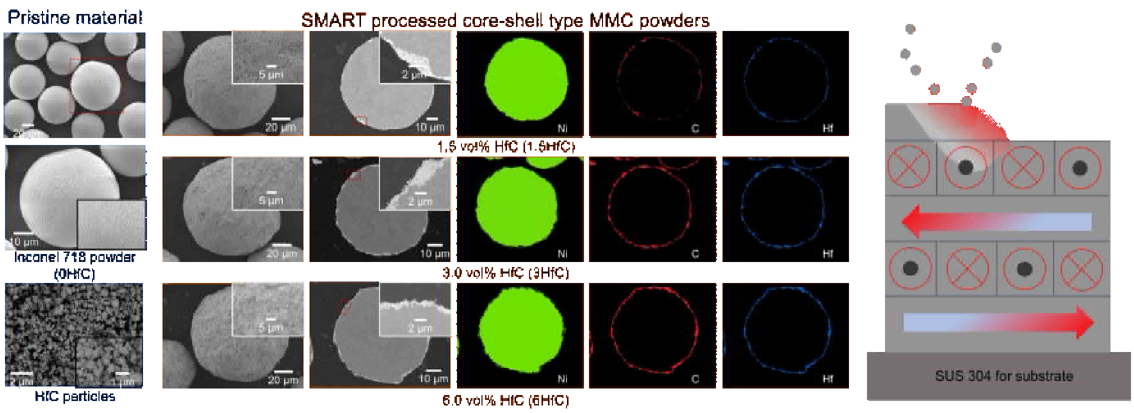

그림. 1. 적층제조용 Inconel 718 분말에 1.5vol.%, 3.0vol.%, 6.0vol.% HfC 강화재를 SMART 공정으로 표면 코팅한 미세조직

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금속 3D 프린터 (L-PBF)로 제조된 316L 및 17-4 PH 스테인리스강의 에너지 밀도 변화에 따른 미세조직 및 기계적 특성 분석

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Effect of Energy Density on Microstructure and Mechanical Properties of L-PBF Processed 316L and 17-4 PH Stainless Steels

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ABSTRACT

레이저 파우더 베드 퓨전(L-PBF)은 복잡한 형상의 금속 부품을 효과적으로 제작할 수 있는 적층 제조 기술로, 공정 조건에 따라 미세조직이 변화하며, 이에 따라 기계적 특성 역시 크게 영향을 받는다. 본 연구에서는 단상 스테인리스강인 316L과 다상 구조를 갖는 17-4 PH 합금을 L-PBF 공정을 통해 제조하고, 주요 공정 변수인 에너지 밀도 변화가 이들 합금의 미세조직 형성 및 기계적 특성에 미치는 영향을 체계적으로 평가하였다.

미세조직 분석은 XRD 및 EBSD 기법을 활용하여 수행하였으며, 기계적 특성은 경도 및 인장시험을 통해 평가하였다. 단상 조직의 316L 소재의 경우, 에너지 밀도 감소에 따라 전위셀 크기가 감소하였으며, 이에 따라 항복강도가 증가하고 인장 변형 특성도 개선되는 경향을 보였다. 이러한 316L에서의 결과를 기반으로 다상 조직을 가진 17-4 PH 합금을 분석한 결과, 전위셀 크기의 감소가 다상 조직에서도 항복강도 변화에 중요한 영향을 미친다는 것을 확인하였다. 또한 17-4 PH 합금에서는 에너지 밀도가 증가할수록 잔류 오스테나이트의 분율이 증가하여, 인장 시 Transformation Induced Plasticity(TRIP) 현상이 활성화되어 우수한 인장 강도와 연성을 나타내었다.

본 연구 결과는 L-PBF로 제조된 단상 및 다상 스테인리스강의 미세조직과 기계적 특성 간의 상관관계를 제시하며, 특히 다상 조직을 가지는 다양한 합금 소재의 적층 제조 시 미세조직 제어 및 공정 최적화를 위한 중요한 기초 자료로 활용될 수 있을 것으로 기대된다.

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적층제조 $L1_2$-강화 고엔트로피 합금의 미세조직 및 기계적 거동

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Microstructural Evolution and Mechanical Behavior of Additively Manufactured $L1_2$-strengthened High-Entropy Alloys

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ABSTRACT

With the advancement of additive manufacturing (AM), increasing efforts are being made to develop new alloys tailored to the unique characteristics of this process. In particular, $L1_2$-strengthened high-entropy alloys ($L1_2$-HEAs) have shown great potential in overcoming the strength–ductility trade-off. However, $L1_2$-HEAs often suffer from the formation of brittle intermetallic phases after aging treatment, primarily owing to Ti segregation at dislocation cell boundaries during AM.

To address these challenges, we designed a new alloy composition with improved FCC–$L1_2$ phase stability and fabricated the alloy in bulk form using a laser powder bed fusion (L-PBF) process. Furthermore, the influence of microstructural evolution on mechanical properties was investigated under four distinct conditions: as-built (AB), direct aging (DA), recrystallized (RX), and recrystallized followed by aging (RA).

Fig. 1 summarizes the microstructures of $L1_2$-HEAs under the various conditions. Electron backscatter diffraction (EBSD) inverse pole figure (IPF) maps revealed strong columnar grains aligned along the build direction in the AB. DA resulted in

partial recrystallization, while the RX exhibited no columnar structures. Scanning transmission electron microscopy (STEM) analysis showed a high density of dislocation cells in the AB. $L1_2$ nanoprecipitates were observed in both DA and RA, confirmed by the $(001)_{L12}$ spots in selected area diffraction (SAD) patterns.

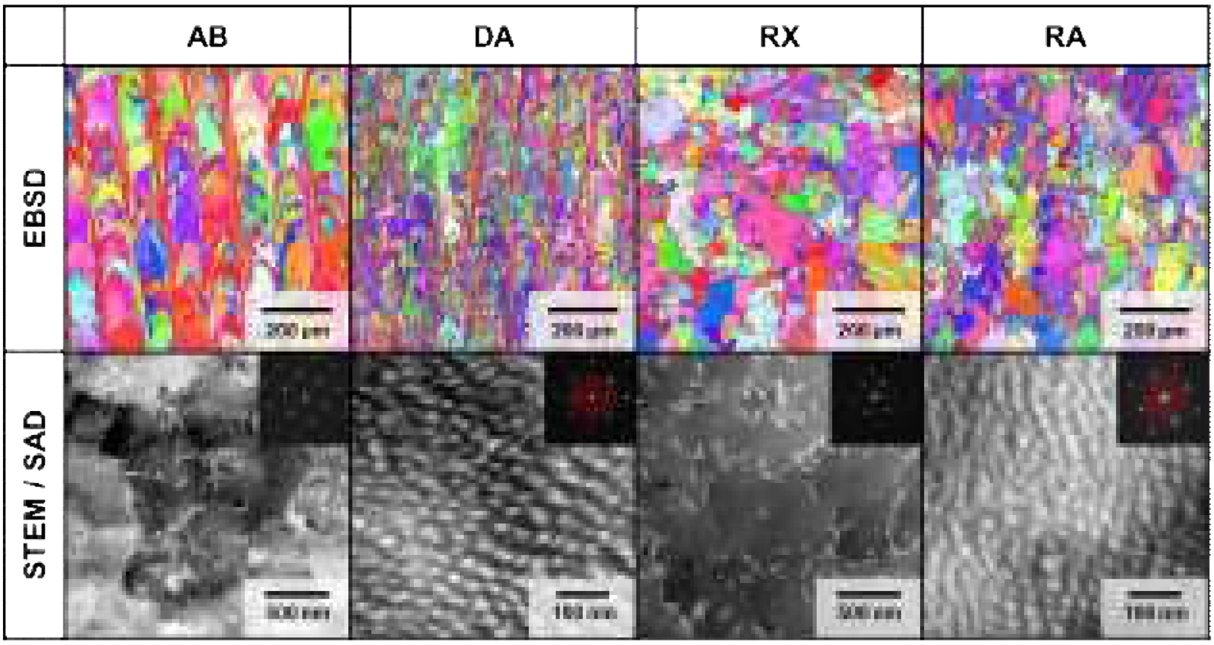

Fig. 1 EBSD and STEM images showing microstructures of AM $L1_2$-HEAs

Tensile engineering stress - strain curves are presented in Fig. 2. The DA exhibited the yield strength of 1115 MPa, ultimate tensile strength of 1565 MPa, and uniform elongation of 18%. Despite the order strengthening by $L1_2$ nanoprecipitates, the strength of RA remained below those of the DA. This difference is likely attributed to the absence of heterostructure-induced hardening in the DA sample. To verify this, loading - unloading - reloading (LUR) tests were conducted to evaluate the evolution of back stress. As shown in Fig. 2, the DA specimen exhibited the highest back stress, indicating that the presence of partially recrystallized grains promotes hetero-induced deformation behavior.

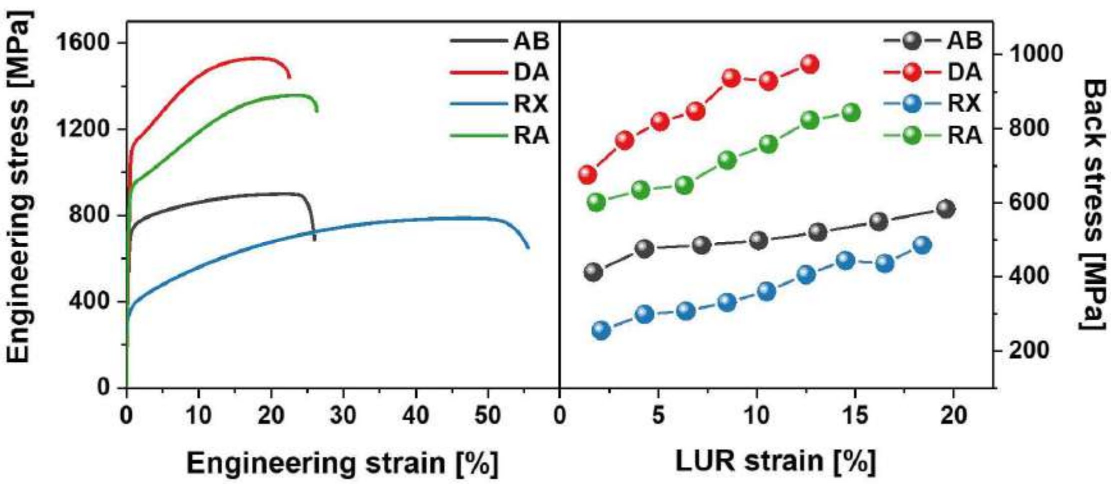

Fig. 2 Engineering strain-stress curves and LUR test results of AM $L1_2$-HEAs

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상장모델링과 평균장 이론 모델링을 활용한 적층제조용 Ni기 초내열 합금 IN738LC 상변화 분석

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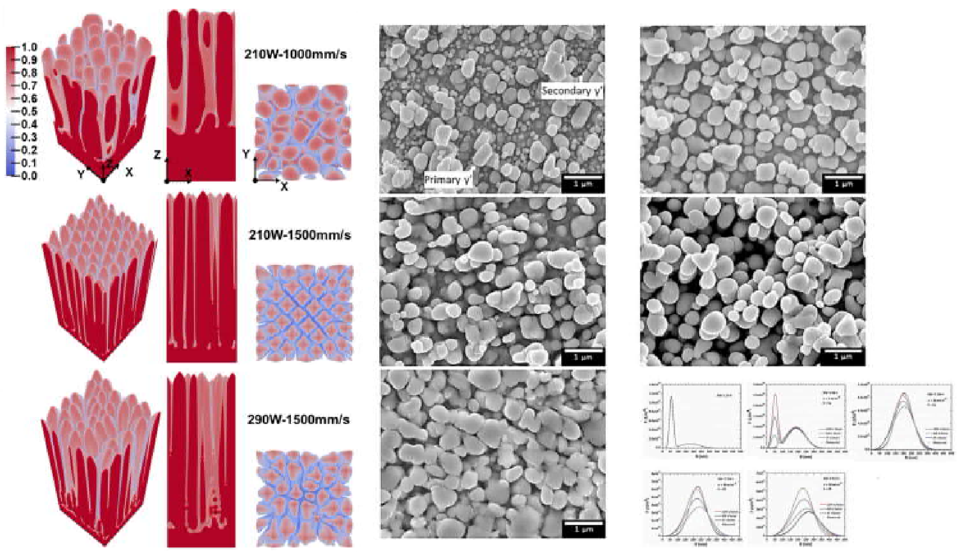
ABSTRACT

We investigate the phase transformations of the IN738LC during additive manufacturing process using phase-field and mean-field modeling techniques. We find that the dendrite impingement is observed at low thermal gradient during solidification, and it decreases the solute segregation at cell boundaries. Thus, MC carbide formation decreases under high laser-power and high scan-speed conditions, which is the optimized combination that minimizes defects such as pores, lack of fusion, micro-cracks. The γ′ coarsening kinetics is also investigated to understand the transition physics of bimodal and unimodal distributions. We find that the γ′ volume fraction is an important parameter in the mean-field modeling, which is slightly higher than the equilibrium value due to non-equilibrium composition of γ-γ′ phases in the additively manufactured superalloy. It is also found that the γ/γ′ interfacial energy and z factor have more influence on the γ′ precipitate coarsening kinetics than the mobility parameter in additively manufactured IN738LC.



<그림> 적층제조용 Ni기 초내열 합금 IN738LC의 (좌) 적층제조 조건에 따른 응고 상변화 (우) 후속열처리 조건에 따른 석출상 조대화

제 39 회 첨단구조재료 심포지엄

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제 3 발표회장

- Session 1
- Session 2

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Al-Cu 주조 합금을 이용한 초음파 용탕 처리에 의한 미세구조 변화의 메커니즘 연구

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Understanding the mechanism of ultrasonic melt treatment in Al-Cu alloys: Microstructural evolution and precipitation behavior

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ABSTRACT

Casting processes are widely used across industries to manufacture complex metallic components, such as aluminum alloys. However, achieving microstructural and compositional homogeneity—critical for ensuring consistent properties and reliable performance—remains a persistent challenge. Among emerging solutions, ultrasonic melt treatment (UST) offers a promising approach by modifying the melt state prior to solidification.

To explore this potential, we investigated Al-10 wt.% Cu binary alloys, a model precipitation-hardened system composed of only α and Θ phases. Samples were processed with and without UST under a range of cooling conditions, from rapid water quenching to ~1 K/s. This design allowed us to systematically assess the influence of UST across different solidification environments.

Our microstructural characterizations using optical microscopy (OM), scanning

electron microscopy (SEM), and electron probe microanalysis (EPMA) revealed that UST significantly enhanced uniformity in both dendritic morphology and Cu distribution within primary-α phases. Notably, these improvements were achieved with less than one minute of treatment, demonstrating the efficiency of the process.

The impact of UST extended beyond solidification, influencing subsequent precipitation behavior. Aging tests, transmission electron microscopy (TEM), and precipitation modeling confirmed that UST altered precipitation kinetics which, in turn, altered mechanical response.

Importantly, the benefits of UST were most pronounced under rapid cooling conditions. At higher cooling rates, untreated samples exhibited substantial inhomogeneity in Cu distribution, while UST-treated samples maintained significantly greater uniformity—emphasizing UST's effectiveness when conventional diffusion is limited.

In summary, this study highlights how UST can fundamentally modify solidification pathways and precipitation behavior, resulting in enhanced mechanical properties. These findings underscore the potential of UST as a rapid, scalable method for achieving alloy homogeneity in aluminum-based systems.

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전류 인가를 통한 알루미늄 용탕 내 Fe계 phase 침전 거동 가속화 연구

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Acceleration of Fe-phase sedimentation in molten aluminum via electrical current application

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ABSTRACT

Aluminum alloys are widely used in the automotive and aerospace industries due to their excellent lightweight properties and mechanical performance. However, the addition of various alloying elements to enhance strength has complicated recycling processes, particularly with regard to the removal of iron (Fe), which forms brittle intermetallic compounds such as β-Al_5FeSi and Al_3 Fe during solidification. These compounds deteriorate ductility and toughness, thus impairing the overall mechanical properties of aluminum alloys. Therefore, developing effective Fe removal techniques is critical for the high-purity recycling of aluminum scrap. Conventional approaches include the addition of precipitating agents followed by gravitational separation, electromagnetic stirring, and centrifugal casting. In this study, a new method was proposed in which a direct current (DC) is applied to the molten aluminum to promote the coarsening and sedimentation of Fe-rich intermetallic phases.

The experiments were conducted using two alloy compositions: Al-3Fe and Al-3Fe-2Sn. The alloys were melted using an induction furnace and cast into sand molds. Immediately after casting, a DC current ranging from 0 to 500 A was applied.

In the Al-3Fe alloy without Sn addition, the application of electric current promoted significant coarsening and sedimentation of Fe phases, with the most pronounced effect observed at 300 A. In the Sn-containing Al-3Fe-2Sn alloy, partial coarsening of Fe phases was observed even without electric current, but effective

precipitation did not occur. However, when Sn was added and current was applied simultaneously, both coarsening and sedimentation of Fe phases were significantly enhanced, particularly at electric currents above 300 A. These results suggest that the Lorentz force induced by the applied current generates convective flow in the molten metal, thereby reducing compositional gradients between the solid and liquid phases and accelerating Fe phase growth via enhanced diffusion.

Unlike Mn and Cr, which form stable compounds with Al and increase the residual alloying content, Sn selectively reacts with Al-Fe phases without forming stable intermetallics with Al itself. This selective behavior allows for more effective Fe removal without compromising recyclability. This study demonstrates that the combination of Sn as a precipitating agent and direct current application provides a promising strategy for controlling Fe impurities in recycled aluminum alloys.

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아노다이징 공정을 통한 타이타늄의 해수부식 저항성 향상 연구

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Tailoring Anodized TiO_2 Films for Corrosion-Resistant Titanium in Alkaline-Seawater Electrolysis

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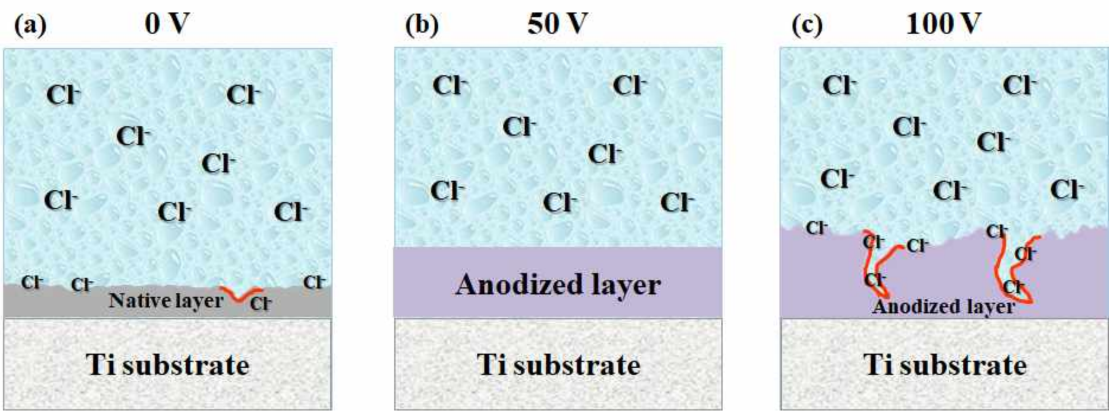
ABSTRACT

This study investigates the anodizing behavior of commercially pure titanium to develop corrosion-resistant and electrically conductive surfaces suitable for alkaline-seawater electrolysis. Titanium specimens were anodized at voltages ranging from 10 to 100 V in a phosphoric-acid electrolyte, and the resulting oxide films were characterized using morphological, electrochemical, and spectroscopic techniques to assess film thickness, corrosion behavior, and surface conductivity. Moderate anodizing voltages, particularly 50 V, produced uniform and compact TiO_2 films that effectively suppressed ion transport and withstood aggressive alkaline chloride environments. Potentiodynamic polarization tests in 1 M KOH + 0.5 M NaCl revealed a significant reduction in the corrosion current density and positive shift in the corrosion potential compared to an untreated surface. Complementary X-ray photoelectron spectroscopy analysis confirmed the suppression of surface hydroxylation and prevention of chloride incorporation, along with the presence of phosphate residues embedded within the oxide, contributing to enhanced chemical stability. Although the corrosion resistance improved with increasing voltage up to 60 V, higher voltages resulted in excessive oxide

growth, structural degradation, and a pronounced decline in surface conductivity. The anodized film formed at 50 V achieved an optimal balance between corrosion protection and electrical functionality, satisfying the dual requirements of chemical durability and electrical conductivity for long-term electrochemical operation. These results provide practical guidance for tailoring the anodization conditions for titanium components used in alkaline-seawater electrolysis systems.



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Al 첨가가 Mg-1Zn-1Y-0.1Mn 합금 판재의 미세조직, 집합조직 변화 및 기계적 특성에 미치는 영향

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The effect of Al element on microstructure, texture evolution and mechanical properties in Mg-1Zn-1Y-0.1Mn alloy sheets

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ABSTRACT

The influence of Al content on the microstructure, texture and mechanical properties of Mg-xAl-1.0Zn-0.1Mn-1.0Y (x=0, 0.1, 0.3, 0.5 and 1.0 wt.%) alloys was investigated. With decreasing Al content, formability at room temperature is dramatically increased. The high formability in low Al containing alloy sheets is mainly due to the weak TD-split texture and the high activity of prismatic <a> slip caused by high amount of dissolved Y elements.

1. 서 론

마그네슘 합금 판재에 강소성 가공 및 합금원소 첨가의 방법으로 집합조직을 약화시킬 수 있고, 이에 따라서 성형성을 향상시킬 수 있다고 알려져 있다. 집합조직 약화 원소로 잘 알려진 희토류 원소는 Mg-Zn합금계에서는 집합조직 약화가 명확히 나타나지만 [1], 유동성과 주조성을 향상시켜주는 원소로 알려진 Al이 첨가된 합금에서는 집합조직 약화 효과를 보이지 않는 것으로 알려져 있다 [2]. 본 연구에서는 Al 첨가로 인하여 Mg-1Zn-1Y-0.1Mn 합금에서 미세조직, 집합조직 및 기계적 성질에 미치는 영향을 연구하고자 한다.

2. 결과 및 토론

그림 1은 Al 첨가량에 따른 소둔처리 후의 IPF 맵을 보여준다. IPF 맵에서 확인할 수 있듯이 Al 원소의 첨가량이 증가할수록 빨간색으로 보이는, 즉 c축이 ND방향과 평행한 결정립의 분율이 크게 증가하는 것을 알 수 있었다. Mg-1Zn-1Y-0.1Mn 합금에서는 적어도 0.3Al까지는 집합조직 약화 효과가 나타남을 확인할 수 있다. 하지만, Al첨가량이 0.5wt.% 이상되면 강한 저면 집합조직을 형성한다는 것을 알 수 있다. 이는 Al 첨가에 의해서 Y의 집합조직 약화효과가 사라짐을 알 수 있다. 집합조직 측정 결과 Al의 양이 0.3wt.% 이하일때는 TD-broad 집합조직을 보이는 반면, Al 첨가량이 0.5wt.% 이상에서는 강한 저면 집합조직 형성을 보여주었다. 0Al, 0.1Al, 0.3Al의 상온 성형성은 9.03 mm, 8.93 mm, 8.07 mm로 매우 우수한 성형성을 보여준 반면, 0.5Al과 1.0Al은 5.07 mm, 3.63 mm로 매우 낮은 성형성을 보여주었다. 2차상 형성의 거동은 0Al에서는 Mg3Zn3Y2상이 주로 나타났으나, 0.1wt.% 이상의 Al이 첨가된 합금들에서는 Al2Y의 주된 2차상으로 확인되었다. 이로부터 집합조직의 변화 효과의 주 요인은 2차상이 아님을 확인할 수 있었다. 기재내에 고용된 합금원소의 양을 분석한 결과에 의해 Y 고용량이 0.5wt.%이상의 Al이 첨가되면 0.14wt.%로 급격하게 낮아짐을 알 수 있었고, 이로인하여 IGMA분석 결과 prismatic <a> 전위의 활성화가 급격히 낮아짐을 확인할 수 있었다. 이는 Al 첨가에 의해서 기지내에 고용된 Y 양이 현저히 줄어들고, 이로인하여 강한 저면 집합조직이 형성되고, prismatic <a> 전위의 활성도를 낮춰 성형성이 줄어들 수 있음을 명확히 보여주었다.

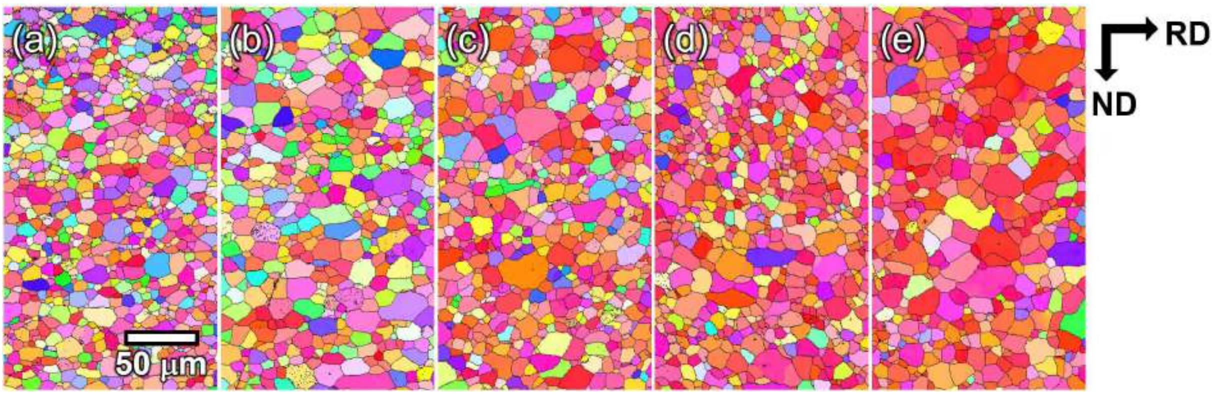

그림 27 (a) 0Al, (b) 0.1Al, (c) 0.3Al, (d) 0.5Al, (e) 1.0Al 합금의 IPF맵

3. 결론

본 연구에서는 Mg-1Zn-1Y-0.1Mn 합금에 Al 첨가량이 0.3wt.%를 초과하게 되면 기지내의 Y 고용량을 현저히 떨어트리고, 이로 인하여 강한 저면 집합조직을 형성할 수 있고, 성형시 prismatic <a> 전위의 활성도를 낮춰 상온 성형성을 급격하게 떨어트릴 수 있음을 밝혔다.

[1] H. Yan, R. Chen, N. Zheng, J. Luo, S. Kamado, E. Han, J. Magnes. Alloy 1 (2013)
[2] R. Pei, Y. Zou, M. Zubair, D. Wei, T. Al-Samman, Acta Mater. 233 (2022)

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발표분야: 경량/항공

7xxx계 합금에서 아연 함량에 따른 인장특성 및 파괴인성 변화

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The effect of zinc content on the tensile properties and fracture toughness in 7xxx series Al alloys

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ABSTRACT

금속 합금에서 강도와 파괴 인성 간의 상충 관계(trade-off)는 오랫동안 해결되지 않은 과제로 남아 있다. 본 연구는 Al-Zn-Mg-Cu 계 합금에서 아연(Zn) 함량이 기계적 특성과 파괴 거동에 미치는 영향을 조사하였다. Zn 함량이 증가함에 따라 η′ 석출물의 밀도가 증가하여 석출 강화가 촉진되며, 그 결과 항복 강도와 인장 강도가 향상된다. 그러나 이러한 강도 향상은 동시에 파괴 인성의 저하를 초래하는데, 이는 높은 Zn 함량이 소성 영역(plastic zone)의 크기를 감소시키고 균열 전파(crack propagation)를 촉진하기 때문이다. 특히 η′ 석출물에 의해 유도된 높은 전위 밀도는 균열 전파를 유도하는 구동력을 제공하며, 미세 석출물에 의해 발생한 변형장(strain field) 또한 이러한 거동에 기여한다. 본 연구 결과는 Zn 함량이 Al-Zn-Mg-Cu 합금의 강도-인성 상충 관계를 조절하는 데 있어 핵심적인 역할을 함을 시사하며, 기계적 성능 최적화를 위한 설계 지침을 제공한다.

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적층제조에 적합한 저비용 고분율 γ′초내열합금 설계 및 변형거동 고찰

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Novel Design and Deformation Behavior of Low-Cost, High γ′ Fraction Superalloys for Additive Manufacturing

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ABSTRACT

Additive manufacturing (AM) is increasingly being highlighted as a key technology in the gas turbine and aerospace industries, offering a viable alternative to the conventional investment casting for producing Ni-based superalloy components. To enhance the temperature capability required for these demanding applications, superalloys must contain a high volume fraction of the γ′ phase, which is achieved by increasing the content of elements like Al and Ti. However, superalloys with a high γ′ volume fraction (typically exceeding 40-50%) are highly susceptible to hot cracking during the rapid heating and cooling cycles of AM processes [1]. Consequently, most current research to date has been focused on low γ′ superalloys such as Inconel 625, 718 and Hastelloy X, which offer excellent AM processability but possess limited high-temperature strength. Moreover, the few existing alloy design efforts have largely relied on empirical, trial-and-error methods. Such approaches have often resulted in compositions containing substantial amounts of costly elements like Ta and Hf, which limits their potential for widespread industrial application [2,3]. In this study, a multi-scale design methodology was employed to address the inherent cracking issues of the reference superalloy CM247LC, aiming to reduce the content of

high-cost elements while preserving its high-temperature strength. Different from the traditional trial-and error approach of optimizing properties by incrementally adjusting elemental compositions, this research utilized large-scale thermodynamic simulations and DFT calculations. This enabled the high-throughput screening and evaluation of alloy candidates based on key thermodynamic properties, including solidus, γ-γ′ lattice misfit, TCP phase fraction, γ′ fraction and overall material cost. To specifically mitigate cracking susceptibility during AM process, two crucial anti-cracking factors such as CSC index and final scheil solidification range were used as primary screening filters. Out of 36,450 candidates, a modified superalloy composition, designated as Cost-reduced and Weldable (CW) 247, was finally selected through experimental ingot screening tests. The new superalloy CW247 was successfully fabricated via selective electron beam melting (SEBM) process without defect such as hot crack, porosity, and lack of fusion. Most importantly, no significant cracks were observed in CW247, as shown in Fig. 1. The heat-treated CW247 alloy possesses a γ′ area fraction of 61%, which is comparable to the reference alloy. Furthermore, the absence of deleterious TCP phase formation after long-term thermal exposure confirmed the excellent microstructural stability of CW247. The superior tensile properties of CW247 at both RT and 871 °C were discussed in terms of deformation mechanism.

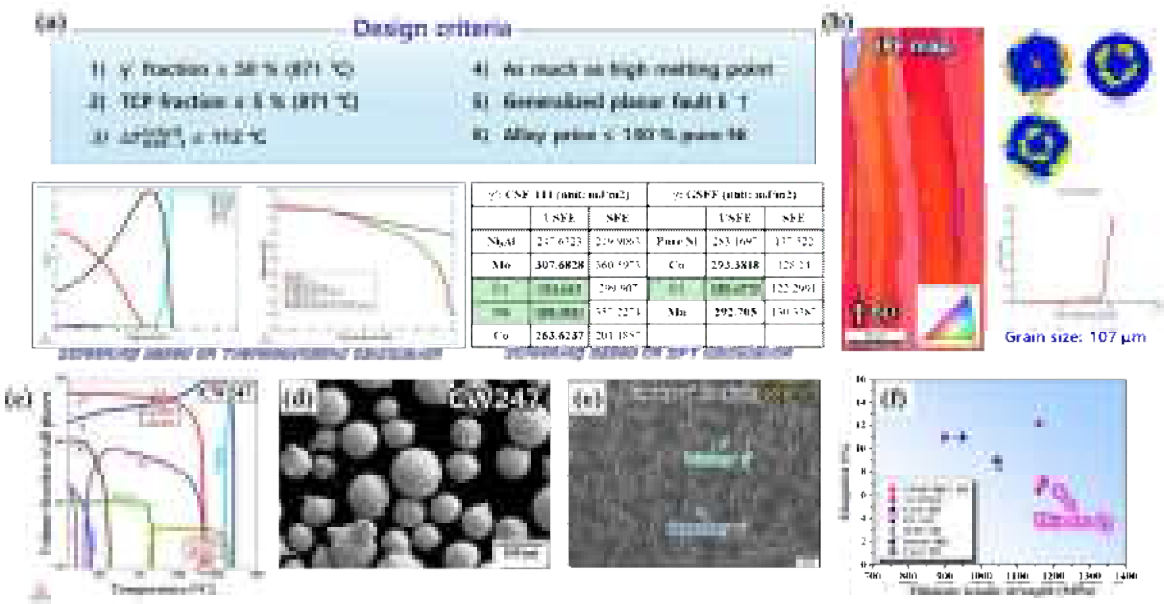

Fig. 1. Newly developed CW247 superalloy showing a good characteristic to AM: (a) Alloy design criteria, (b) As-built microstructure (crack-free columnar grain), (c) predicted equilibrium, phase fraction, (d) powder morphology, (e) γ/γ′ microstructure. and (f) superior tensile property

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원자로용기용 저합금강 전자빔용접부의 후열처리 공정영향 평가

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Evaluation of Post-Weld Heat Treatment Effects on Electron Beam Welds in Low-Alloy Steel for Reactor Pressure Vessels

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ABSTRACT

세계적으로 에너지수요 증가와 기후변화 대응을 위한 탄소중립 실현의 필요성이 커짐에 따라, 소형 모듈형 원자로(Small Module Reactor, SMR)에 대한 관심이 높아지고 있다. SMR은 주요 계통을 하나의 일체형 용기에 집약한 구조로 설계되어 주요 부품 및 기기를 공장에서 제작한 후 현장에서 설치함으로써 건설비용과 기간을 크게 절감할 수 있는 장점이 있다. 국내에서는 전기출력 170 MW급의 혁신형 SMR(i-SMR) 개발이 진행되고 있다. 그러나 대형원전에 비해 출력이 낮은 SMR의 경제성과 운송 효율성을 확보하기 위해서는 원자로 압력용기(Reactor Pressure Vessel, RPV)와 같은 대형기기의 경량화와 경제성 확보가 필수적이다. 이를 위해 혁신형 SMR에는 기존 대형 원전의 원자로용기에 적용된 SA508 Gr.3 Cl.1 저합금강 보다 높은 강도를 가지는 SA508 Gr.3 Cl.2 저합금강을 적용하는 방향으로 설계가 진행되고 있다. 또한 전체 제작기간의 단축을 위해 기존의 다중패스 SAW(Submerged Arc Welding, SAW) 공정 대신 단일패스가 가능한 전자빔용접(Electon Beam Welding, EBW) 공정을 대형기기 제작에 적용하고자 한다. 혁신형 SMR의 원자로용기는 최대 250 mm 이상의 두께를 갖는 것으로 예상되고 있으며, 이를 단일패스로 용접할 수 있는 초대형 EBW 시스템이 개발되고 있다. 그러나, 현재까지 압력용기 제작에 EBW 공정이 실제로 적용된 사례는 없으며, EBW에 최적화된 후열처리(Post-Weld Heat Treatment, PWHT) 조건이나 관련 규정이 부족하다. 현재 원자로압력용기 제작 관련 규정에서 혁신형 SMR 대형기기 제작에 EBW 공정이 적용되더라도 기존 SAW 공정에 적용되는 후열처리 공정이 그대로 적용되어야 한다. 따라서 고강도 저합금강인 SA508 Gr.3 Cl.2 강의 전자빔용접부에 적합한 최적의 후열처리공정을 도출하기 위

한 사전연구가 필요하다.

본 연구에서는 현재 원자로압력용기에 적용되고 있는 SA508 Gr.3 Cl.1 저합금강을 이용하여 40 mm 두께의 전자빔용접부를 제작하고, 후열처리 조건에 따른 미세조직 및 기계적특성 변화를 평가하였다. 용접 후에는 기존 PWHT 공정인 610℃/30시간 열처리를 적용하여, SA508 Gr.3 Cl.2 저합금강 모재 수준으로 인성 회복이 가능한지를 확인하였다. 또한, Cl.1 저합금강의 최소 템퍼링 온도를 고려하여 630℃/30시간 조건에서도 후열처리를 수행하였으며, 용접부 미세조직 균질화 및 용접부 제거 효과를 확인하기 위해 기존 상용원전 원자로용기 제작 공정에 적용되는 퀜칭-템퍼링의 품질열처리도 추가로 실시하였다. 후열처리 조건 영향을 확인하기 위해 광학현미경 및 주사전자현미경을 활용하여 용접부와 열영향부의 미세조직을 관찰하고, 마이크로 비커스 경도시험을 통해 용접부 위치에 따른 경도 분포를 확인하였다. 또한, 상온 및 압력용기 가동온도인 288℃에서 인장시험을 수행하고, -120℃ ~ 120℃의 온도범위에서 충격천이특성, -150℃ ~ -30℃의 온도범위에서 천이영역 파괴인성을 평가하였다. 이후 EBSD 분석을 통해 결정립 크기를 측정하고, 고배율 SEM 이미지로 석출물을 정량화하여 파괴인성에 미치는 영향을 고찰하였다.

As-welded 상태의 용접부 및 열영향부는 저온변태상의 형성으로 인해 높은 경도와 강도, 낮은 파괴특성을 나타내었다. PWHT 적용은 기지의 연화와 잔류응력의 완화로 인해 강도는 감소하였으나 충격인성이 향상되었다. 그러나 PWHT 온도가 증가할수록 석출물이 조대화되며, 이에 따라 천이온도가 상승하고 천이영역 파괴인성은 저하되는 경향이 나타났다. 한편, 품질열처리를 적용한 경우에는 미세조직의 완전한 균질화가 이루어지지 않아 충격천이특성은 모재 대비 다소 낮게 나타났다.

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Cu 첨가에 따른 페라이트/마르텐사이트계 내열강의 630°C 크리프 거동

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Creep Behavior at 630°C of Ferritic/Martensitic Heat-Resistant Steel with Cu Addition

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ABSTRACT

This study aims to enhance the high-temperature properties and creep resistance of 10% Cr ferritic/martensitic steels used in steam turbine rotors and blades in combined heat and power systems. By replacing Co with Cu, which performs a similar role but at a lower cost, an alloy was designed to improve high-temperature strength and maintain performance under prolonged exposure to elevated temperatures. Creep tests were conducted for the reference (Cu-free) and modified (Cu-added) steels at 630°C under various stress conditions to evaluate the effect of Cu addition. Notably, the Cu-containing steel exhibited superior creep resistance for long-term creep under low stress conditions, especially at 145 MPa, where its life was increased up to 12,733 hours which is 14% improved compared to the Cu-free steel. Microstructural analysis using Electron Back-Scattered Diffraction (EBSD) revealed that the Cu-containing steel exhibited stable prior austenite grain size and better retention of martensite lath structure during long-term creep. Transmission electron microscopy (TEM) and atom probe tomography (APT) confirmed that Cu-rich precipitates formed both at the grain boundaries and within the grains played a crucial role in suppressing grain coarsening and delaying recovery, thereby maintaining a high dislocation density. XRD data analysis using the Modified Williamson-Hall (MWH) and Modified Warren-Averbach (MWA) methods demonstrated that the dislocation density of the Cu-free steel decreased by 81%, while that of the Cu-containing steel decreased by only 66% after long-term creep under 145 MPa. This study highlights the importance of copper as an effective substitute for cobalt in improving the high-temperature properties of ferritic/martensitic steels for turbine applications, especially under prolonged low-stress conditions.

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고엔트로피 합금의 고온 인장 특성에 미치는 붕소 첨가의 영향

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Effect of Boron Addition on the High Temperature Tensile Properties of High Entropy Alloys

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ABSTRACT

To enhance high-temperature tensile properties, the addition of boron to high-entropy alloys (HEAs) has been actively investigated. Boron promotes grain refinement through a grain boundary pinning effect induced by precipitates; however, excessive boron can lead to the formation of borides along grain boundaries. In this study, we examined the high-temperature tensile behavior and microstructural evolution of two HEA specimens with different boron contents (B50: 50 ppm, B500: 500 ppm). Both specimens exhibited fine and coarse hcp-structured μ phases, with the B50 specimen showing a higher volume fraction of coarse μ phase compared to B500. Atom probe tomography analysis revealed that boron segregates at the μ phase boundaries, effectively suppressing their growth. Interestingly, despite its higher boron content, the B500 specimen exhibited superior ductility at high temperatures relative to B50. This suggests that crack initiation occurs predominantly at μ phase boundaries due to severe stress localization, highlighting the importance of μ phase size control. These findings demonstrate that boron addition can effectively regulate μ phase growth and improve the high-temperature tensile performance of HEAs.

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온도수용성이 우수한 Re-free 단결정 초내열합금 개발 연구

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Development of a Re-free single crystal superalloy with enhanced temperature capability

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ABSTRACT

Single crystal superalloys are among the most advanced metallic structural materials capable of withstanding extreme mechanical stress at elevated temperatures. These alloys are key materials for the hot-section components of gas turbines. Since gas turbine efficiency increases with higher turbine inlet temperatures, the major technical challenge in developing high-efficiency turbine engines lies in securing materials capable of enduring extreme centrifugal forces at the highest operating temperatures. Therefore, the development of single crystal superalloys with enhanced temperature capability is expected to drive technological advances in both power-generation and aircraft gas turbine engines.

The generational classification of single crystal superalloys is largely determined by the content of rare elements such as rhenium (Re) and ruthenium (Ru), with Re playing a particularly critical role in improving high-temperature properties. However, Re is an extremely expensive element produced by only a few countries, and its increasing content results in reduced cost competitiveness and heightened supply chain risks. As a result, recent research trends have focused on reducing the amounts of expensive rare elements like Re and Ru while improving the alloys' high-temperature performance. This global movement is not limited to advanced

Western countries; China is also actively investing in the optimization of Re and Ru content to achieve material self-sufficiency in single crystal superalloys.

In this study, the high-temperature creep properties of a Re-free single crystal alloy developed by the Aerospace Materials Research Center at the Korea Institute of Materials Science (KIMS) were evaluated and compared with those of commercial alloys. The developed Re-free alloy exhibited approximately 30°C higher temperature capability than CMSX-4, which contains 3 wt.% Re, while the cost of alloying elements was only about 40% of CMSX-4. These alloys are currently undergoing further optimization, and they are expected to contribute significantly to the localization of core materials for gas turbines.

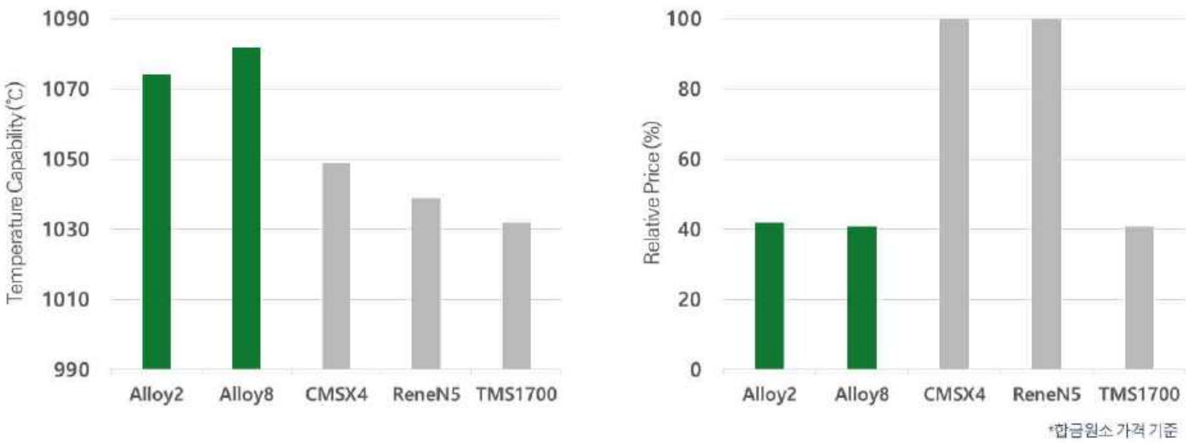

Figure 1. Comparison of temperature capability and relative price of commercial and developed alloys

제 39 회 첨단구조재료 심포지엄

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제 1 발표회장

- Session 3
- Session 4

Proc. of the 39th Conference on Advanced Structural Materials
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30MnB5 핫스탬핑강 저항 점 용접부 파괴인성 영향인자 및 파단 메커니즘과 미세조직 제어를 통한 십자인장강도 개선

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Fracture Toughness Factors and Failure Mechanisms in Resistance Spot Welded 30MnB5 Hot-Stamping Steel with Microstructural Improvement Strategies

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ABSTRACT

최근 자동차 산업에서는 연비 개선과 충돌 안전성 확보를 위해 초고강도 핫스탬핑강의 적용이 확대되고 있다. 이와 같은 고강도 강재는 높은 기계적 강도를 갖지만, 저항 점 용접시 전단인장강도 대비 낮은 십자인장강도를 가지며, 취성 파단이 발생하는 모습을 보인다. 이는 소재 강도 증가에 따른 파괴인성의 저하와 밀접한 관련이 있다. 초고강도 강재의 접합 신뢰성을 확보하기 위해서는 용접부 파괴 인성에 영향을 미치는 주요 인자를 규명하고 이를 제어할 수 있는 미세조직 개선 전략이 필요하다. 본 연구에서는 1.2mm 두께의 30MnB5 핫스탬핑강 겹치기 저항 점 용접부를 대상으로 합금원소 편석, 미세조직, 공정 변수가 용접부 파괴인성에 미치는 영향 및 파단 거동의 상관관계와 용접 후 열처리를 통한 미세조직 제어로 인한 파단 거동 변화를 바탕으로, 파괴 인성 향상을 목표로 한 펄스 스케줄을 설계하였다.

Keywords: 저항 점 용접, 핫스탬핑강, 파괴인성, 십자인장강도

Introduction

초고강도강은 차량 경량화와 충돌 안전성 강화를 위해 널리 적용되고 있으나, 저항 점 용접 시 전단인장강도에 비해 낮은 십자인장강도를 보이며 취성 파단이 발생한다. 이는 파괴인성 저하와 관련이 있으며, 용접부 내 Columnar 조직 합금원소 편석과 조직의 구조로 인한 Fusion Zone(FZ) 파단[1], 용접 과정에서 용접부 주위에 형성되는 2상 영역으로 인한 국부적인 편석 및 취성 조직[2], 입계로의 Phosphorous 편석[3] 등이 보고되어 왔으

나 용접부 파괴인성 영향인자와 이에 대한 미세조직적 해결 방안에 대한 연구는 아직 미비한 실정이다. 본 연구에서는 1.2mm두께의 30MnB5 핫스탬핑강을 대상으로 저항 점 용접부 파괴인성 영향인자 및 미세조직 제어를 통한 십자인장강도 개선을 목표로 하였다.

Results and discussion

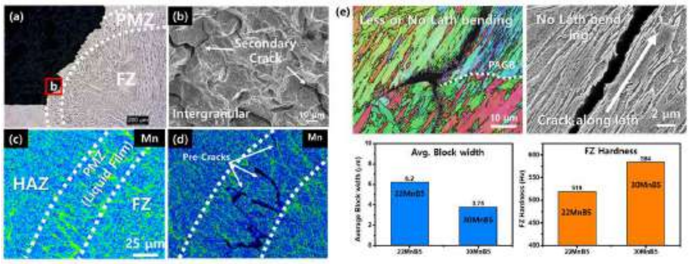

Fig. 1. (a)십자인장시험 후 파단 단면;(b)SEM 파단면;(c)(d)용접부 EPMA 결과 및 편석부 발생 Pre-Crack;(e)균열 전파 거동EBSD, SEM 및 22MnB5와의 미세조직 특성 비교

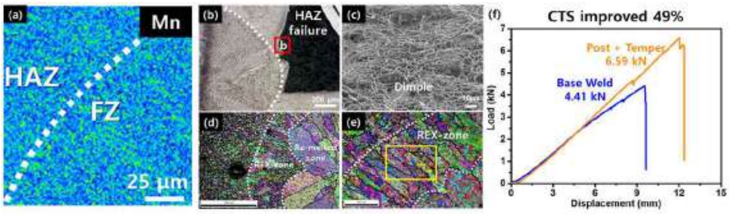

Fig. 2. (a)PMZ 최소화 펄스 적용 후 EPMA 결과;(b)개선 펄스 적용 후 파단 단면;(c)SEM 파단면;(d)(e)용접부 Grain refinement EBSD 결과; (f)기존 용접 조건과 개선 펄스 적용 후 Load-Displacement 비교

저항 점 용접된 30MnB5 용접부는 용접 과정에서 Partially Melted Zone(PMZ)을 형성하여[2] Fusion Zone(FZ) 외곽에 합금원소 편석을 심화시킨다. 이로인해 파단은 PMZ의 Liquid Film 구조에서 Pre-Crack을 발생시켜 Intergranular파단을 유도하고, PMZ를 통해 균열이 쉽게 전파된다. 또한 22MnB5대비 높은 탄소 첨가량으로 인해 Block 직경 및 경도 증가로 Slip Activation Energy가 증가해 균열 전파 시 에너지를 흡수하지 못해 취성파단을 보임을 Fig. 1에서 확인 가능하다. 후열처리를 통해 결정립 미세화 및 편석 완화 달성 시 Heat Affected Zone(HAZ)로 파단 경로가 변화하였으며, 이를 기반으로 PMZ 편석 최소화, Slip Activation Energy 저감 및 FZ내 Columnar 조직 제어를 목표로 설계한 펄스 스케줄은 PMZ 편석 최소화, FZ 결정립 미세화 및 FZ 템퍼링으로 구성하였으며, 적용 후 PMZ 편석 저감, FZ 결정립 미세화, FZ 템퍼링 효과로 인해 연성 파단 및 HAZ 파단을 유도해 기존 조건 대비 49% 증가한 십자인장강도를 Fig. 2.에서 확인 가능하다.

Conclusion

1. 용접부 PMZ 편석, 높은 Slip Activation Energy 및 FZ내 Columnar 조직은 용접부 파괴인성을 감소시켜 십자인장강도를 저하시킨다.
2. 위 세 가지 영향인자를 펄스를 통해 제어한 후, 십자인장강도는 49% 증가하였다.

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구오스테나이트 입계의 방위차가 중탄소 마르텐사이트강의 수소유기 입계 균열 전파에 미치는 영향

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Influence of prior austenite grain boundary misorientation on hydrogen-induced crack propagation in a medium carbon martensitic steel

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ABSTRACT

This study investigates the effect of prior austenite grain misorientation (θ_γ) on hydrogen-induced intergranular cracking along prior austenite grain boundaries (PAGBs) in a medium-carbon tempered martensitic steel (SCM435). Using EBSD analysis and prior austenite orientation reconstruction, the misorientation of martensite ($\theta_{\alpha'}$) and austenite (θ_γ) at PAGBs was compared between fractured boundaries and all observed boundaries (Fig. 1). The results show that low-angle martensite segments ($\theta_{\alpha'}$ < 10°) at PAGBs help prevent intergranular cracking. These low misorientation segments are more likely to form when θ_γ is less than 10° (L-PAGB) or greater than 45° (H-PAGB), under certain conditions.

To identify the conditions for H-PAGBs to form low misorientation martensite, an interrupt quenching method was used to observe the early stage of

martensite nucleation. The findings suggest that martensite needs to follow the Kurdjumov–Sachs (KS) orientation relationship not only with the austenite grain it grows from, but also with the neighboring grain across the boundary. This condition —called "double KS OR"—is often satisfied in martensite that forms at the early stage of transformation. This highlights the importance of variant selection in forming

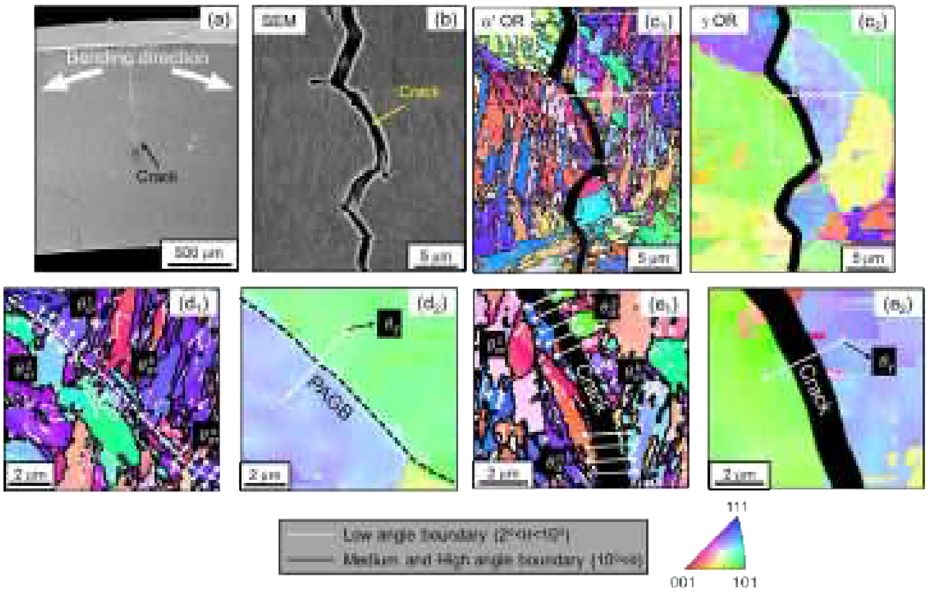

Fig. 1. Observation of a hydrogen-induced crack. (a) Low magnification SEM micrograph, (b) High magnification SEM micrograph, (c_1) Martensite orientation map, (c_2) Reconstructed austenite orientation map, (d_1) Martensite orientation map of non-fractured PAGB, (d_2) Reconstructed austenite orientation map of non-fractured PAGB, (e_1) Martensite orientation map of fractured PAGB, (e_2) Reconstructed austenite orientation map of fractured PAGB (Reproduced from [1]).

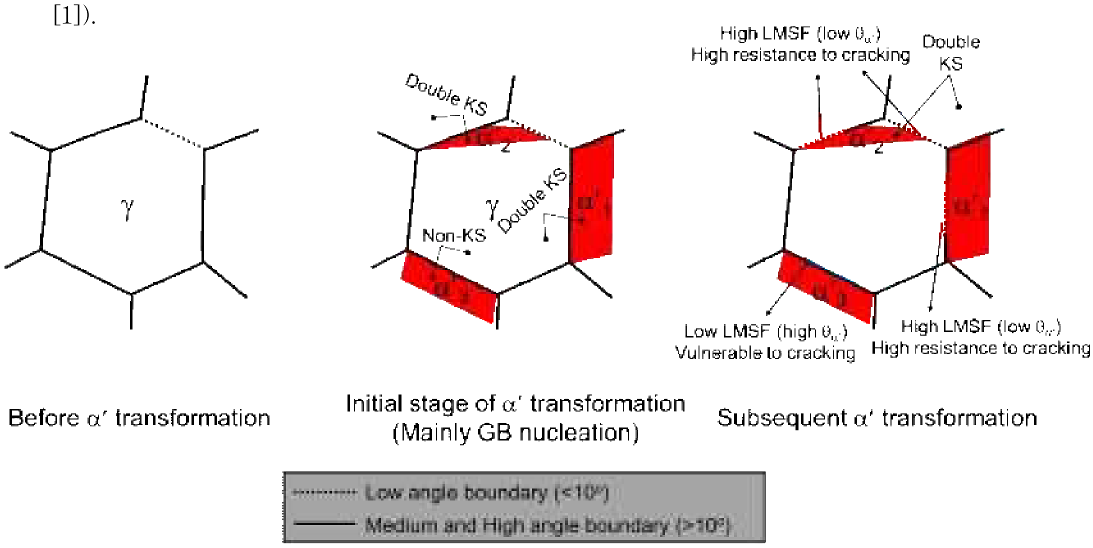

Fig. 2. Schematically illustrated microstructure evolution during martensitic transformation depending on austenite misorientation angle (Reproduced from [1])

[1] J.H. Kim, G. Miyamoto, A. Shibata, T. Hojo, M. Koyama, Y. Zhang, T. Furuhara, Acta Materialia (2024) 120036.

low misorientation martensite segments at PAGBs

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우주선 구조용 3중층 High-Mn/Invar/High-Mn 강 복합재 설계

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Design of a Three-layered High-Mn/Invar/High-Mn Steel Composite for Structural Applications in Spacecraft

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ABSTRACT

To ensure the long-term use and fuel efficiency at launch of satellites, lightweight alloys with high strength and toughness (e.g., Al and Ti) are commonly used in their components. Moreover, the wide temperature variations in operational orbits, ranging from approximately -200 °C to 100 °C, could lead to cyclic thermal expansion. Thus, components such as antennas and connecting rods should be composed of materials with a low coefficient of thermal expansion (CTE), such as invar alloy or CFRP composite, to ensure precise signal transmission and the rigidity of the satellite body. Consequently, satellite components are now composed of relatively complex combinations of lightweight alloys and low-CTE materials, resulting in intricate manufacturing processes and component structures. Herein, we have fabricated a steel laminate that achieves a remarkable balance between strength, toughness, and low-CTE properties. The laminate plate was produced using a clad teeming technique, combining invar alloy and advanced high-strength steels.

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수소 주입 방식과 온도 변화가 BCC 및 FCC 금속의 파괴 특성에 미치는 영향

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Effects of Hydrogen Charging Methods and Temperature on the Fracture Behavior of BCC and FCC Metals

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ABSTRACT

Hydrogen embrittlement is a phenomenon in which the mechanical properties of metallic materials deteriorate significantly when exposed to hydrogen environments, posing a critical challenge to the structural integrity of materials used for hydrogen storage and transportation. To prevent this phenomenon and ensure hydrogen embrittlement resistance, it is essential to establish a thorough understanding of hydrogen-metal interactions, including adsorption, penetration, diffusion, and trapping. These interactions are strongly affected by the hydrogen charging method and temperature, necessitating a systematic investigation that considers both variables. However, most previous studies have addressed these variables individually, and comprehensive investigations into their combined effects remain insufficient. Moreover, although BCC (body-centered cubic) and FCC (face-centered cubic) metals exhibit distinct hydrogen embrittlement behaviors due to their different crystal structures, comparative studies between the two metal types under varied hydrogen charging methods and temperature conditions remain limited. In this study, low-carbon linepipe steel (API X65) and 316 stainless steel were selected as representative materials for BCC and FCC metals, respectively, to investigate how different hydrogen charging

methods and temperatures influence their hydrogen embrittlement resistance. Using notched specimens, the hydrogen embrittlement resistance of two steels was quantitatively evaluated under various hydrogen charging methods, including ex-situ (pre-charging) and in-situ electrochemical charging, at two distinct temperatures of 25℃ and 55℃. Fracture behavior at both the notch root and center regions of the notched specimen was systematically investigated, and the hydrogen embrittlement mechanism was elucidated using thermal desorption spectroscopy (TDS) and the hydrogen micro-print technique.

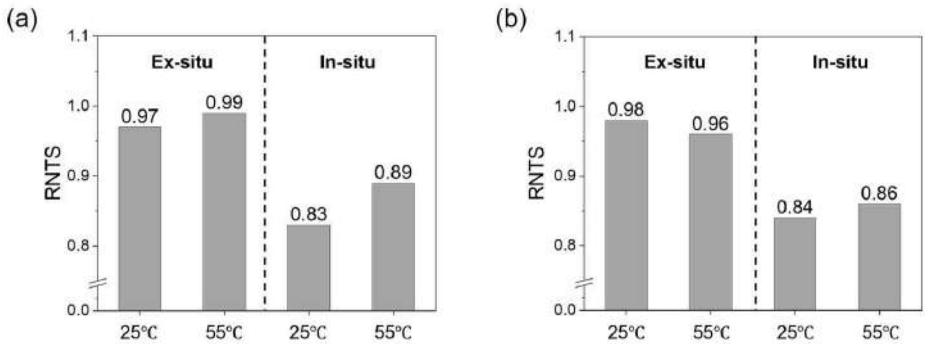

Fig. 1. Relative notch tensile strength (RNTS) of (a) API X65 steel and (b) 316 stainless steel under different hydrogen charging methods (ex-situ and in-situ) and temperatures (25℃ and 55℃).

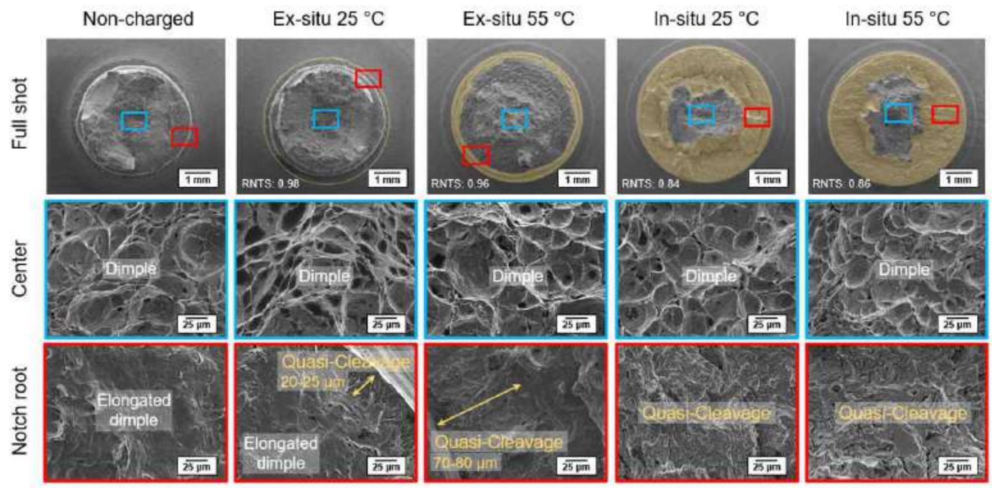

Fig. 2. SEM fractographs of notched 316 stainless steel specimens subjected to various hydrogen charging methods (non-charged, ex-situ, and in-situ) and temperatures (25℃ and 55℃). The brittle fracture areas of the specimens are highlighted in yellow.

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PEMFC 시스템에서의 스테인리스강 및 티타늄 금속 분리판의 부식 저항성과 수소 투과 거동에 미치는 귀금속 코팅의 영향

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Investigation of Corrosion Resistance and Hydrogen Permeability in Stainless Steel and Titanium Alloy in Bipolar Plates with Noble Metal Coatings for PEMFC System

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ABSTRACT

The development of durable and efficient proton exchange membrane fuel cells (PEMFCs) has increased the demand for metallic bipolar plates with superior electrical conductivity, corrosion resistance, and durability. Mostly, rerritic stainless steel, austenitic stainless steel, and titanium alloys are commonly considered candidates due to their mechanical robustness and chemical stability. However, under the highly acidic and humid conditions of PEMFC operation, these metals are susceptible to corrosion and hydrogen permeation, which can deteriorate fuel cell performance and compromise safety.

In this study, the influence of noble metal coatings on both corrosion resistance and hydrogen uptake behavior was systematically investigated for commercial stainless steels and a titanium alloy. Thin noble metal layers were deposited by sputtering to enhance surface conductivity and passivation properties. Electrochemical Impedance Spectroscopy (EIS) and polarization measurements were employed to evaluate

corrosion characteristics, while the Devanathan–Stachurski electrochemical technique was used to assess hydrogen permeation behavior under simulated PEMFC electrolyte conditions.

As shown in Fig. 1, Nyquist analysis from EIS results revealed that Au coatings significantly increased the charge transfer resistance (R_{ct}) and overall impedance, indicating a remarkable enhancement in corrosion resistance across all tested materials. Each plot compares the impedance response of bare specimens with those coated with an Au noble metal layer, illustrating the significant increase in charge transfer resistance and improved corrosion resistance imparted by the Au coating. The largest impedance improvement was observed in overall materials. Furthermore, hydrogen permeation tests confirmed that noble metal coatings effectively suppressed hydrogen uptake.

The results clearly demonstrated that noble metal coatings significantly improved both corrosion resistance and suppression of hydrogen uptake across all tested materials. Among the coatings, Pt exhibited slightly superior performance compared to Au, effectively reducing hydrogen ingress while providing excellent electrochemical stability. These findings confirm that noble metal coatings offer a dual benefit—enhanced corrosion protection and minimized hydrogen absorption—thereby presenting a promising approach for optimizing the durability and performance of next-generation metallic bipolar plates in PEMFC applications.

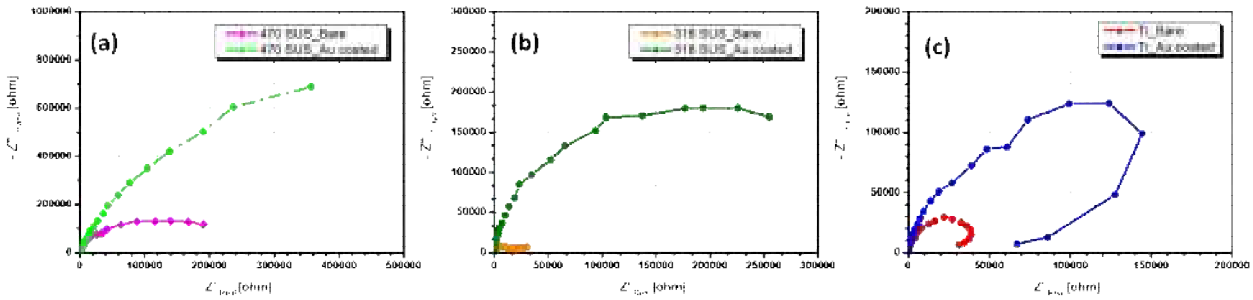

Fig. 1. Nyquist plots obtained from Electrochemical Impedance Spectroscopy (EIS) measurements for (a) SUS 470, (b) SUS 316L, and (c) Ti alloy bipolar plates, tested in 0.5 M H_2SO_4 solution over a frequency range of 0.1–100,000 Hz.

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γ′-Ni_3(Ti, Al) 석출 강화 인바 합금에서 시효 온도가 충격인성에 미치는 영향

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Influence of aging temperature on the impact toughness in γ′-Ni_3(Ti, Al) precipitation-strengthened Invar alloy

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ABSTRACT

This study investigates the influence of aging temperature on the impact toughness of a γ′-Ni_3 (Ti, Al) precipitation-strengthened Fe-38.7Ni-3.5Co-1.0Ti-1.2Al (wt.%) Invar alloy. Aging between 500 °C and 600 °C promoted the formation of coherent γ′ precipitates through both discontinuous precipitation (DP) along grain boundaries and continuous precipitation (CP) within grain interiors. These precipitates contributed to substantial strengthening while maintaining satisfactory ductility. Notably, the alloy sustained high impact toughness (~350 J) up to 550 °C. However, a significant drop to ~200 J was observed following aging at 600 °C. Microstructural analysis indicated that the hardness disparity between DP and CP regions became pronounced at 600 °C, promoting localized strain accumulation and

void initiation along DP interfaces during impact loading. This shift in the dominant energy absorption mechanism—from plastic deformation to void-induced fracture—was identified as the primary cause of toughness degradation. These findings highlighted the inherent trade-off between strength and impact toughness in precipitation-hardened Invar alloys and provided valuable insight for optimizing their microstructural design in structural applications.

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저방사화강의 고온 크리프 거동에 미치는 수소 영향 연구

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Effect of Hydrogen on High-Temperature Creep Behavior of Reduced Activation ferritic-martensitic Steel

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ABSTRACT

Fusion energy is a clean and promising power source capable of addressing global warming and environmental concerns. As the world's largest international scientific collaboration, the International Thermonuclear Experimental Reactor (ITER) aims to demonstrate the scientific and technological feasibility of nuclear fusion. In the DEMO reactor design, more than 85% of the in-vessel surface/volume surrounding the plasma will be occupied by structural materials, and six blanket prototypes will be tested. Reduced activation ferritic/martensitic (RAFM) steel, a 9Cr-based alloy, has emerged as a key structural material for cladding and outer tubes in advanced fast reactor fuel assemblies. RAFM steel exhibits superior resistance to radiation-induced swelling, high thermal conductivity, and a low coefficient of thermal expansion. However, fusion environments contain large amounts of deuterium and tritium as plasma fuels, which can diffuse into structural components—especially plasma-facing components (PFCs) and blanket modules.

Neutron irradiation creates lattice defects that act as hydrogen trapping sites, thereby enhancing the susceptibility to hydrogen embrittlement (HE). Moreover, the extreme operating conditions of fusion reactors—particularly high temperatures (500 -

700 °C)—accelerate hydrogen diffusion and trapping. Consequently, the accumulation of hydrogen isotopes within the metal can eventually lead to brittle fracture, posing a critical challenge to the structural integrity of fusion reactor components.

Therefore, in this study, high-temperature (550 °C) creep tests were conducted under both Ar and H_2 gas atmospheres for comparison. The creep fracture time drastically decreased from 5468 h in Ar to 409 h in H_2, indicating a severe degradation in creep resistance. Notably, the steady-state creep strain rates increased significantly, while the total creep strain remained constant. This suggests that the recovery process was greatly accelerated, disrupting the balance between work hardening and dynamic recovery. It is thus considered that hydrogen strongly affects dislocation mobility at elevated temperatures. From a microstructural perspective—including the width of lath boundaries, dislocation substructure, and carbide evolution—the role of hydrogen was analyzed to understand its effect on creep deformation mechanisms under fusion-relevant conditions.

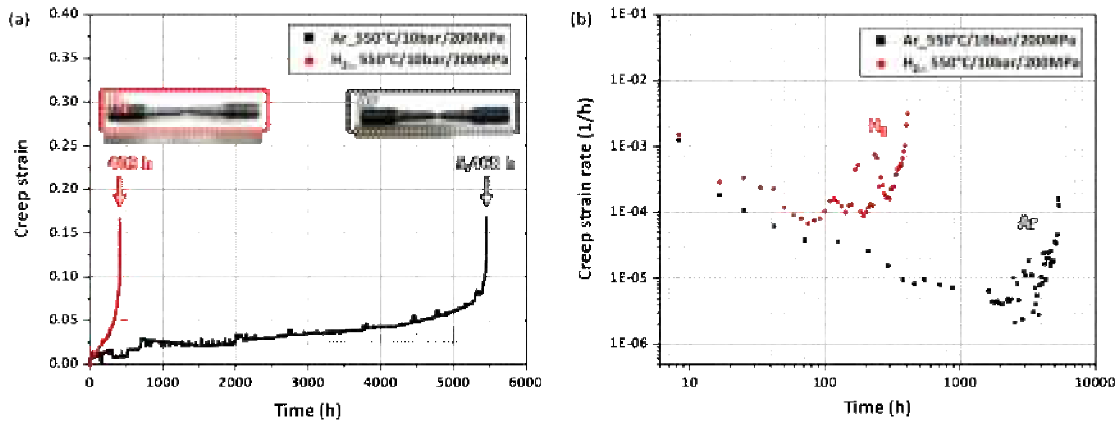

Fig. Long-term creep behavior of RAFM steel: (a) Creep strain as a function of time, and (b) creep strain rate as a function of time under an applied stress of 200 MPa at 550 °C in 10 bar of Ar and H_2 gas atmospheres, respectively.

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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

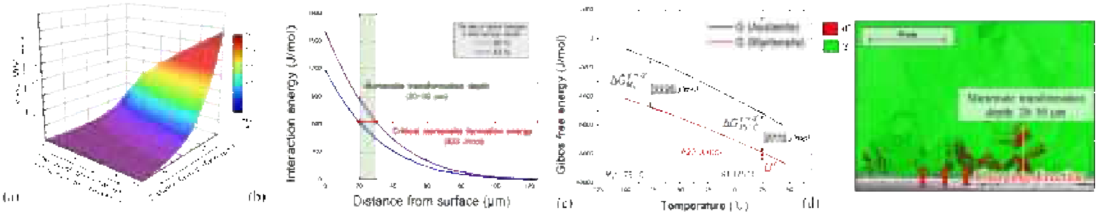
Martensitic transformation is a diffusionless change from austenite to martensite, typically triggered by mechanical, thermal, or chemical stimuli. While mechanical transformation is well-known, electrochemical mechanisms remain unclear. This study examines CHC-induced transformation, focusing on the 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/cm^2, 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 μm depth (Figure 1). Thermodynamic analysis indicated that 53–90% of hydrogen exists as H^+ under CHC, supporting its dominant role via electro-mechanical coupling.



Figrue. 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 ℃ and -78 ℃ (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).

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- Session 3
- Session 4

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3차원 내부구조 및 나노기계적 특성 분석을 통한 Si - Al 기반 합금 분말의 조성에 따른 구조적 안정성 평가

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Three-Dimensional Structural and Nanomechanical Characterization of Si - Al Based Alloy Powders: Influence of Composition on Phase Distribution and Stability

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ABSTRACT

Silicon (Si) is considered a promising next-generation anode material for lithium-ion batteries due to its high theoretical capacity (~3,579 mAh/g), nearly 10 times greater than that of graphite. However, the severe volume expansion (~300%) during lithiation/delithiation causes particle fracture, unstable solid electrolyte interphase formation, and rapid capacity degradation. Alloying Si with mechanically supportive elements, particularly aluminum (Al), has been proposed as a strategy to mitigate these issues. In this study, three types of Si - Al based alloy powders with varying Al content were synthesized via atomization.

To investigate their structural and mechanical stability, we analyzed internal microstructures, including phase distribution in 3D. Furthermore, TEM and EDS were used to identify phases and phase-specific crystallographic features, and nanoindentation mapping was conducted to quantify the mechanical properties of individual phases such as Si-rich, Al-rich, and intermetallic regions.

The results show that increased Al content leads to finer Si grains and a greater fraction of Al-rich intermetallic phases, resulting in a decrease in average hardness. However, the mechanical softening of Al-rich regions causes localized stress concentration, which may lead to structural degradation during cycling. This was

correlated with electrochemical behavior where samples with higher Al content exhibited suppressed β-LiAl → α-Al phase transformation and faster capacity fade after 10–20 cycles. Additional analysis revealed a significant drop in Li-ion diffusion coefficients in Al-dominant regions, further highlighting the impact of phase composition on transport properties.

This study demonstrates that not only the electrochemical contribution of Al but also its effect on internal stress distribution and phase-level mechanical properties must be carefully considered in Si–Al alloy design. The integration of 3D structural analysis and nanomechanical characterization provides critical insight into the compositional optimization of alloy-based anodes, serving as a foundational step toward predictive modeling of swelling behavior and long-term performance.

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나노인덴테이션을 활용한 극한표면 손상분석

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Analysis of Damage at Ultra-shallow Depth using Nanoindentation Technique

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ABSTRACT

원자력 발전소와 같이 중성자 조사 또는 부식 환경에 지속적으로 노출되는 소재는 안전을 위해 수백 mm 이상의 두께를 가짐에도 불구하고 초기 손상은 수 마이크로미터 미만의 매우 얇은 극한 표면에 국한되는 것이 일반적이다. 비록 전체 두께 대비 손상된 영역의 두께 비율이 매우 낮음에도 불구하고 손상 정도가 크면 크랙이 생성될 수 있으며, 생성된 크랙에 의해 전체 시스템이 파손될 수 있다. 따라서 초기 손상 단계에서부터 손상 정도에 대한 분석이 필수적이다. 그러나 기존 연구들은 투과전자현미경을 사용하여 손상 정도를 분석하기 때문에 시편 준비 및 분석 과정이 매우 어렵고 비용도 많이 소요되는 문제가 있다. 이에 본 연구에서는 비파괴적히며 시험 과정이 매우 간단한 나노인덴테이션 시험법을 사용하여 극한 표면에서의 조기 손상을 분석하는 연구를 수행하였고, 이를 통해 극한 표면에서의 손상 깊이를 유추하는 방법을 제시하였다.

Acknowledgement
이 성과는 한국수력원자력(주)과 지방자치단체(울산)의 지원으로 수행된 연구이며(2025), 또한 2025년도 정부(과학기술정보통신부)의 재원으로 한국연구재단의 지원을 받아 수행된 국책연구사업(No. RS-2022-00156205)임.

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명료한 결정입계를 얻기 위한 딥러닝 모델 구축과 학습 Data 효과 검토

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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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ABSTRACT

This study explores advanced AI-based methods for detecting ambiguous grain boundaries in optical microstructure images. We applied various deep learning models, including U-Net-based CycleGAN, transfer learning, and self-supervised learning, to enhance boundary visibility. Training data included experimental, literature-based, and synthetic microstructure images. Our approach enables the prediction of grain boundaries that are invisible or unclear in raw images. These techniques markedly improve identification accuracy, offering robust solutions for automated metallographic analysis.

1. 서론

미세조직 내 결정입계의 정확한 검출은 재료의 역학적 특성 및 신뢰성 평가에 핵심적인 역할을 한다. 하지만 광학현미경 사진에서는 입계가 불분명하거나 노이즈, 대조도 한계 등으로 인해 자동 검출이 매우 어렵다. 최근 딥러닝 기반 인공지능 기법이 영상 분석 분야에서 뛰어난 성과를 보임에 따라, 이를 조직사진 분석에도 적극적으로 적용하려는 시도가 이루어지고 있(1-3)다. 본 연구에서는 CycleGAN, U-Net, 전이학습 등 다양한 딥러닝 모델을 활용하여 불명확한 입계의 명료화와 예측 정확도 향상을 시도하였다. 이를 통해 실제 현장의 다양한 조직 데이터에도 적용 가능한, 신뢰도 높은 자동 결정입계 검출

방안을 제시하고자 한다.

2. 학습 Data 와 적용 방법

- 학습 Data
  - 학습의 범용성을 얻기 위해 다양한 품질, size, 재질 등 사전 정보를 갖지 않는 intenet 상에서 확보한 소량의 광학현미경 사진과 사진을 기반으로 만들어진 grain boundary Mask image : 13장
  - 인공적으로 만들어진 noize image, image 및 mask image set : kaggle data(4)
- Image 전처리 : Grayscale, CHAHE, GaussianBlue, Normalization
- 검토 모델 : U-net model, CycleGAN 모델, VGG16 사전 학습 모델

3. 결과 및 요약

다양한 종류의 data를 예측할 수 있도록 학습을 실시하였고, 성능 향상을 위해 다양한 모델 및 시험 data 뿐 아니라 기본적 augmentation 기법 적용등 다양한 조건에서 모델 최적화를 진행하였다.

그림 1은 그 일부 결과를 보여주는 것으로 기본적인 U-net 모델을 사용해도 상당한 예측 성능을 확보할 수 있다. 현미경 사진에 보이지 않는 grain boundary를 예측해서 가시화 성과에 대해서도 보고할 예정이다.

실제적으로는 현장 상황을 반영한 정확한 image 및 mask data를 이용한 모델 학습이 진행될 경우 더 정확한 grain boundary를 찾아 낼 수 있게 될 것이다.

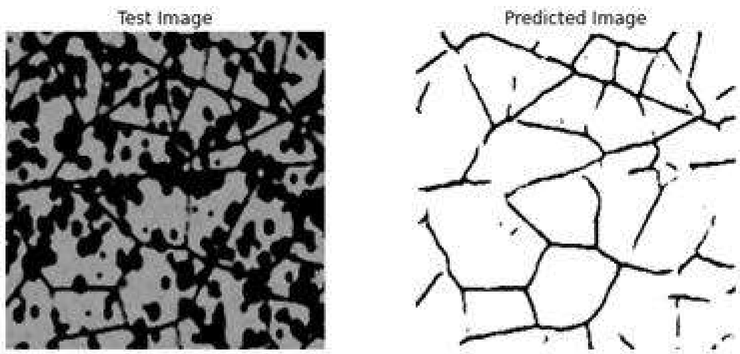

그림 1. Test image를 통해 예측된 grain boundary image(U-net 적용)

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변형 및 온도 이력을 고려한 미세조직 기반 소성 이방성 모델 개발 및 응용

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Strain path and temperature history dependent microstructure-based anisotropic hardening model and its applications

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ABSTRACT

As the demand for lightweight structure and body materials in the automotive industry grows, accurately modeling the mechanical behavior of metals under complex loading histories becomes increasingly important. This study introduces a novel mesoscopic-scale modeling approach to describe the loading path and temperature-dependent plastic hardening behavior of steel. The proposed model incorporates key microstructural mechanisms - such as the yield point phenomenon and dynamic strain aging (DSA) - to efficiently capture plastic hardening responses across a range of temperatures. To account for temperature-dependent variations in the Bauschinger effect under loading and reverse loading condition, anisotropic hardening is formulated based on simplified dislocation polarization theory. The framework enables practical calibration of plasticity over a temperature variation, accurately considering the evolution of anisotropic hardening at load reversal. By integrating microstructural changes into a phenomenological plasticity model, the study offers a physically grounded method for predicting mechanical behavior in various metal forming applications.

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Grade 1 순수 티타늄 판재의 소성이방성 거동에 대한 결정소성 모델 기반 접근

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Prediction of anisotropic flow in pure titanium Grade 1 sheet via crystal plasticity modeling

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ABSTRACT

To investigate the anisotropic plastic response of commercially pure titanium (CP-Ti), a crystal plasticity finite element method (CPFEM) has been established for Grade 1 CP-Ti sheets with a thickness of 0.1 mm. CP-Ti, which is a hexagonal close-packed (HCP) metal, exhibits pronounced tension-compression asymmetry and distinct stress-strain behavior depending on the loading direction. These characteristics are attributed to deformation twinning and the limited number of slip systems. To accurately reflect such mechanisms, the developed model incorporates twinning and detwinning phenomena, as well as plastic slip occurring in twinned regions. A volume-averaged homogenization scheme is employed, wherein the evolving volume fractions of twinned domains are continuously updated based on the activation of twinning and detwinning systems. Comparison with experimental results validates the model's capability to reproduce both the anisotropic mechanical behavior. This modeling approach provides a robust foundation for exploring the plastic deformation mechanisms of titanium under complex loading paths.

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열간 등방압 공정 적용을 통한 적층제조된 중엔트로피 합금의 결함 제어 및 액화헬륨 온도에서의 기계적 불안정성 해석

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Utilizing a hot-isostatic pressing controlling pore defect in direct energy deposited CoCrNi medium-entropy alloy and its mechanical stability at liquid helium temperature

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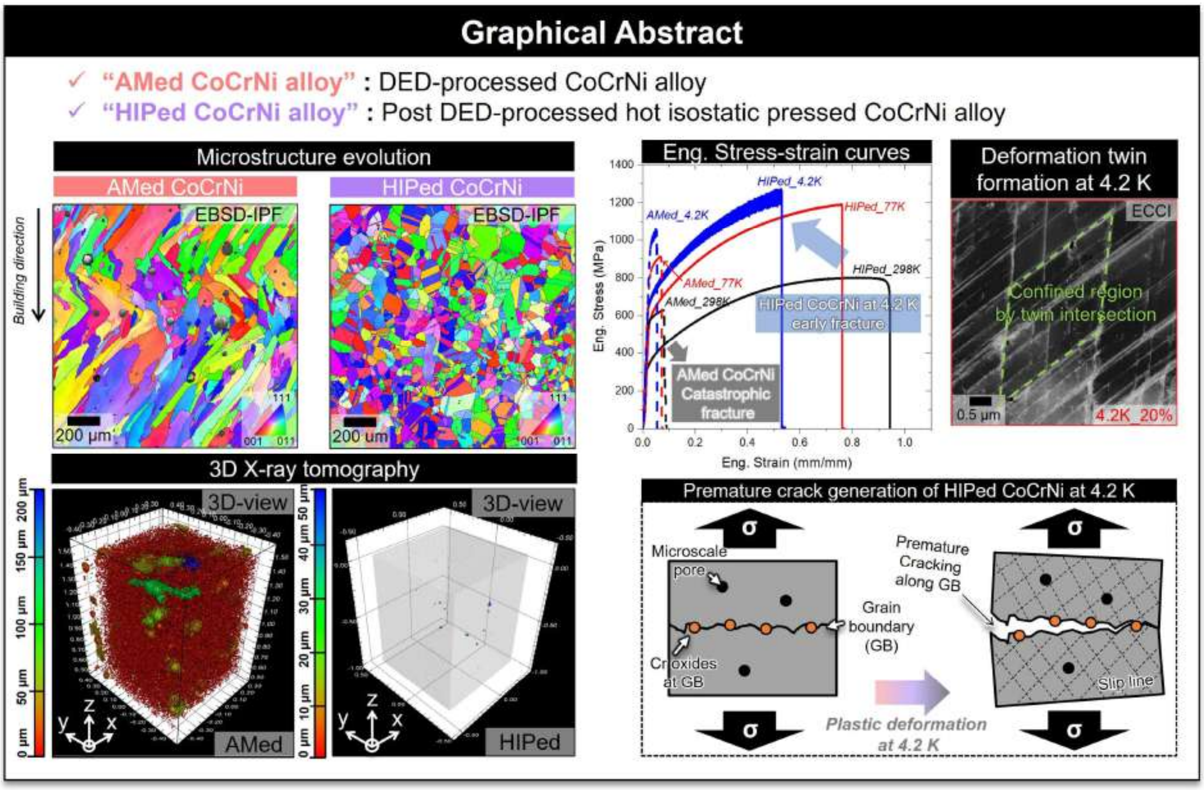
ABSTRACT

At a surprisingly fast pace, applying additive manufacturing (AM) methods in metals or alloys has gained intensive interest owing to many advantages that enable the design of complex structural components with high performance. However, the AM products result in the formation of manufacturing defects, which causes mechanical degradation in extreme environments. Here, we systematically investigated the effect of hot-isostatic pressing (HIP) treatment on microstructure and mechanical stabilities of additively manufactured CoCrNi medium-entropy alloys fabricated by direct energy deposition (DED) at ambient and cryogenic temperatures (e.g., 298 K, 77 K, and 4.2 K). HIP treatment enables the facilitation of microstructure homogeneity and structural densification. Poorly limited ultimate tensile strength (UTS) and total elongation (T.E) were found in DED-processed CoCrNi, whereas the HIP-treated CoCrNi exhibited excellent UTS×T.E synergies. Our findings provide great insights into the structural/mechanical stabilities of effect on HIP treatment in DED-processed CoCrNi at near absolute zero temperature.



Graphical Abstract
✓ "AMed CoCrNi alloy" : DED-processed CoCrNi alloy
✓ "HIPed CoCrNi alloy" : Post DED-processed hot isostatic pressed CoCrNi alloy
Microstructure evolution
AMed CoCrNi
HIPed CoCrNi
Building direction
EBSD-IPF
200 μm
Eng. Stress-strain curves
HIPed_4.2K
HIPed_77K
HIPed_298K
AMed_4.2K
AMed_77K
AMed_298K
HIPed CoCrNi at 4.2 K early fracture
AMed CoCrNi Catastrophic fracture
Eng. Stress (MPa)
Eng. Strain (mm/mm)
Deformation twin formation at 4.2 K
ECCI
Confined region by twin intersection
0.5 μm
4.2K_20%
3D X-ray tomography
3D-view
AMed
HIPed
Premature crack generation of HIPed CoCrNi at 4.2 K
σ
Microscale pore
Grain boundary (GB)
Cr oxides at GB
Premature Cracking along GB
Slip line
Plastic deformation at 4.2 K

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적층제조로 제작된 경사형 내식 경량철강의 계면특성 연구

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Microstructural evolution and properties at the interface and base region of an additively manufactured functionally graded corrosion-resistant lightweight steel

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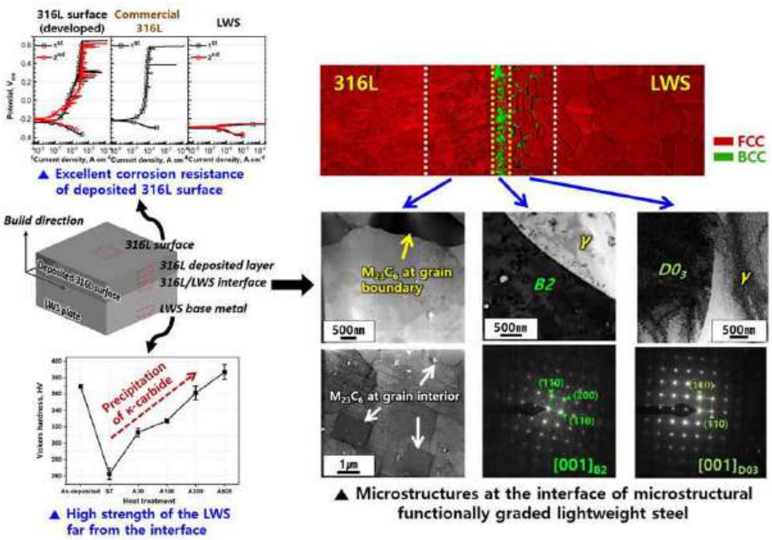
Keywords: Functionally graded materials, Additive manufacturing, Lightweight steel, 316L stainless steel, Phase transformation

ABSTRACT

Functionally graded materials (FGMs) are characterized by gradual changes in composition and/or structure within a single component, which influence the resulting

microstructure and properties. This enables FGMs to overcome conventional trade-offs, such as those between strength-ductility or between mechanical properties-corrosion properties. The lightweight steel (LWS) used in this study is based on the Fe-Mn-Al-C system and consists of a fully austenitic structure. When aging the LWS, superior strength-ductility balance can be achieved through the precipitation of nano-sized κ-carbides within the austenite matrix. In addition, the low mass density of LWS due to its high amount of Al makes it a promising condidate for lightweight structural applications. Despite these advantages, LWS has relatively poor corrosion resistance compared to commercial stainless steel, which may limit its broader application. To overcome this limitation, 316L stainless steel powder was additively manufactured onto the LWS sheets using the Powder Bed Fusion (PBF) process. After PBF, Hot Isostatic Pressing (HIP) was conducted to enhance the corrosion resistance of deposited 316L surface reducing porosity. Solution treatement and aging were performed to homogenize the microstructure of each base region and to develop a hard-matrix in the LWS region, while maintaining the corrosion resistance of the 316L surface. Meanwhile, the interface region between LWS and 316L exhibited distinct microstructural evolution and mechanical properties compared to the base regions of each alloy during heat treatment, which was attributed to the interdiffusion of alloying elements such as C, Al, and Ni, as confirmed by electron probe microanalysis (EPMA). Here, we characterized the microstructural evolution depending on each heat treatment stage through scanning electron microscopy (SEM), electron backscattered diffraction (EBSD), transmission electron microscopy (TEM) analysis, and atom probe tomography (APT). The mechanical property changes were evaluated by Vickers hardness and nano-indentation tests.



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WAAM 공정으로 제조된 Al-Mg 합금의 기계적 이방성에 미치는 층간 결합의 영향

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Interlayer Integrity and Mechanical Anisotropy of WAAM-Processed Al-Mg Alloys

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ABSTRACT

Wire Arc Additive Manufacturing (WAAM) has gained significant attention for fabricating large-scale aluminum alloy components, owing to its high deposition rates, minimal material waste, and cost-effective equipment requirements. Its applicability in structural parts for aerospace and transportation is particularly promising. However, the formation of porosity during multilayer deposition remains a critical challenge, often resulting in pronounced mechanical anisotropy and compromised structural integrity.

This study conducts a comprehensive comparison of the microstructure, porosity evolution, and mechanical performance of two WAAM-fabricated aluminum alloys: Al-5356 and an Al-Mg-Sc-Zr variant. The Al-Mg-Sc-Zr alloy exhibited refined grains (~14 - 18 μm) and significant precipitation strengthening due to the formation of Al_3 (Sc,Zr,Ti) dispersoids. Nonetheless, it suffered from pronounced interlayer porosity averaging 1.02%, predominantly located along layer boundaries. This led to a substantial reduction in vertical mechanical performance, with ultimate tensile strength decreasing from 333.1 MPa (horizontal) to 225.8 MPa (vertical), and elongation dropping from 25.3% to 6.0%.

In contrast, the Al-5356 alloy retained a coarser grain structure (~95 μm) but

exhibited minimal porosity (0.02%) and showed consistent mechanical properties irrespective of loading direction. These results highlight that, although microalloying improves intrinsic alloy strength, the primary cause of anisotropy in WAAM-fabricated aluminum alloys is the spatial concentration of interlayer pores. The findings emphasize the need for improved interlayer bonding and gas control strategies to fully harness WAAM's potential for structural aluminum applications.

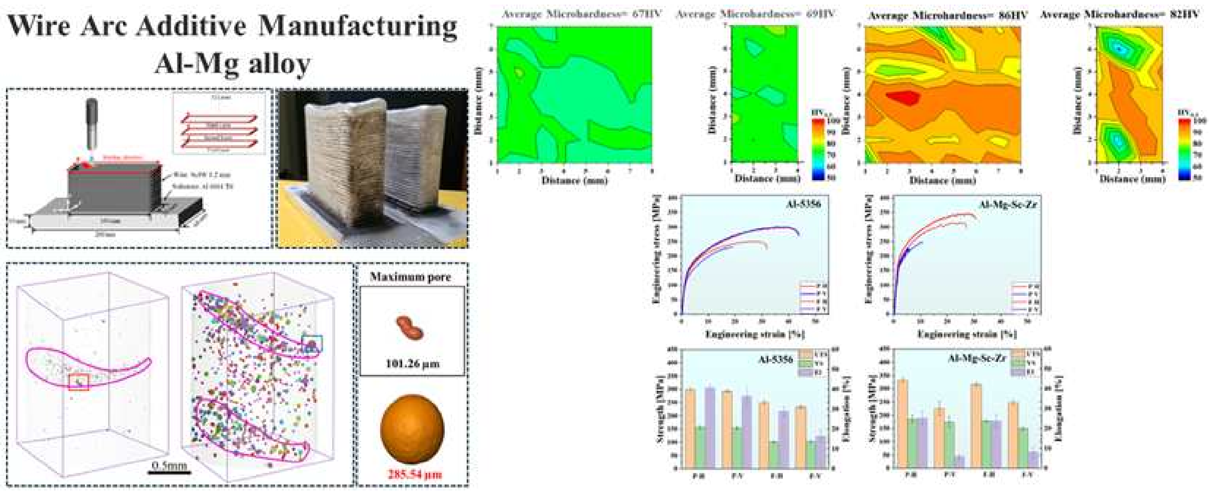

Fig. 1. Schematic of the WAAM process and fabricated Al-Mg alloy specimens (left top), along with representative pore distribution and maximum pore size obtained from XCT analysis (left bottom). The right side presents the distribution of Vickers microhardness across the build direction, engineering stress–strain curves, and comparative mechanical properties for WAAM-fabricated Al-5356 and Al-Mg-Sc-Zr alloys.

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레이저 분말 베드 융합 공정을 활용한 고강도 알루미늄 합금의 적층 제조 및 기계적 특성 분석

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Additive Manufacturing of High Strength Aluminum alloys by using Laser Powder Bed Fusion and Its Mechanical Properties

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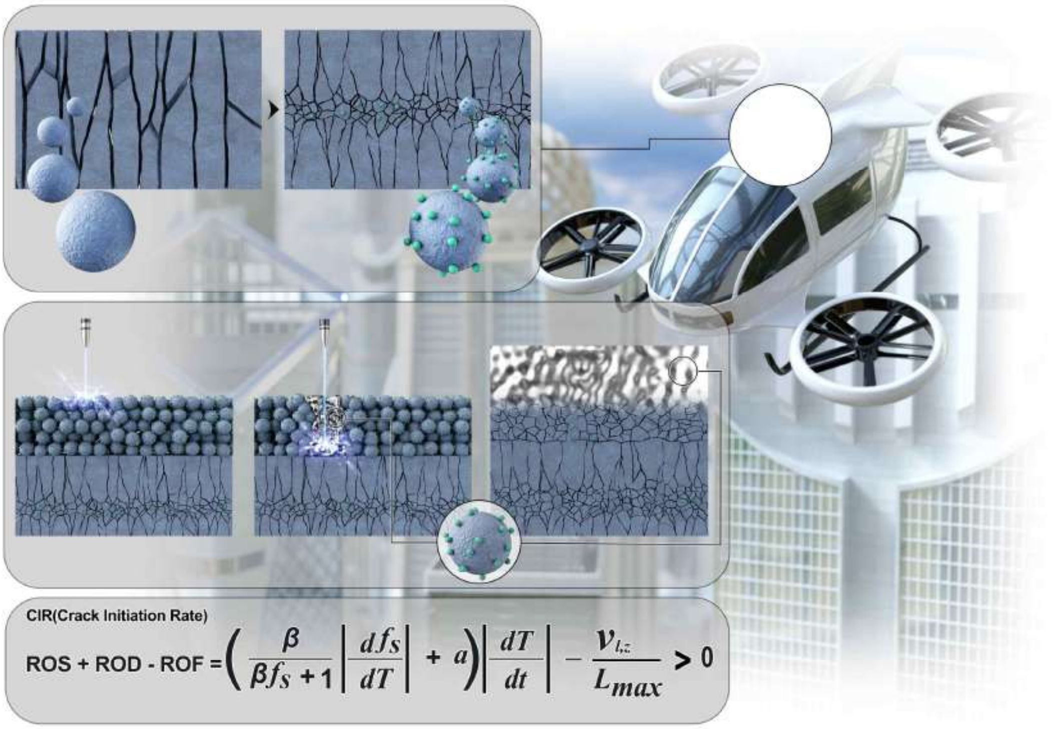
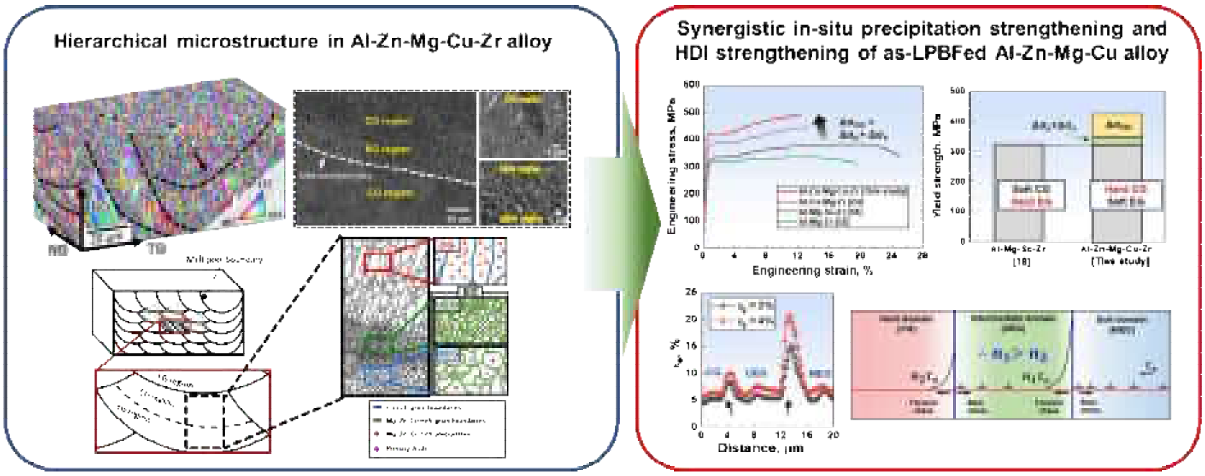
ABSTRACT

Solidification cracking is a major barrier to the additive manufacturing of precipitation-hardenable Al-Zn-Mg-Cu alloys. In this study, we demonstrate that the formation of equiaxed grains (EGs) through ZrH_2 inoculant addition and energy-density control can effectively suppress cracking during laser powder bed fusion (LPBF). A solidification cracking model is proposed, where crack healing is promoted by remelting-induced liquid backfilling under appropriate thermal conditions. This approach enables the fabrication of crack-free Al-Zn-Mg-Cu components, which were previously considered difficult to process via LPBF. Following the successful suppression of cracking, we further investigate the microstructural architecture and mechanical performance of the as-built alloy. The resulting heterogeneous grain structure, comprising coarse columnar grains (CGs) and multi-scaled EGs, enhances strength via hetero-deformation-induced strengthening. In particular, local strain gradients within the EG regions promote additional hardening, resulting in high strength even without post-heat treatment. These findings suggest that controlling solidification behavior not only prevents cracking but also enables microstructure-driven strengthening in Al alloys processed by additive manufacturing.

GRAPHICAL ABSTRACT





제 39회 첨단구조재료 심포지엄
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- Session 3
- Session 4

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적층제조 304L 스테인리스강의 초극저온 기계적 물성

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ABSTRACT

본 연구는 레이저 파우더 베드 융합(LPBF) 공정에서 산소 농도(0.2%)를 정밀하게 제어하여 제조한 SS304L 스테인리스강의 기계적 특성과 미세조직을 상온 및 극저온(77 K, 4 K)에서 체계적으로 평가하였다. 실험 결과, LPBF로 제조된 SS304L은 동일 합금의 인발재 대비 상온에서 약 336 MPa, 4 K에서 최대 398 MPa에 이르는 항복강도(YS) 향상을 보였다. 또한, 본 연구의 LPBF SS304L은 기존 보고된 LPBF SS304L 대비 상온 기준 약 64 MPa의 추가적인 강도 상승을 달성하였다. 이러한 강도 증가는 제어된 산소 농도에 기인한 산화물 분산 강화 효과와 더불어, 결정립계 강화 및 전위 강화에 의한 결과로, 연성 손실은 미미하였다. 아울러, 변형 유발 마르텐사이트 변태(SIMT)는 상온에서 관찰되지 않았고, 극저온에서도 인발재 대비 그 양이 현저히 감소하였으며, 이는 높은 전위 밀도 및 질소 안정화 오스테나이트의 영향으로 해석된다. 4 K에서 관찰된 급격한 변형(Jerk flow) 현상은 낮은 열전도도에 기인한 소성 변형 중의 단열 가열 효과로 설명된다. 유한요소 해석 결과, LPBF 공정에서 용융 금속의 체류시간은 0.0137초로 매우 짧았으며, 산화물 입자는 주로 용융풀 표면에서 불균일 분포 생성되어 마랑고니 대류에 의해 균일하게 분산됨이 밝혀졌다. 본 연구 결과는 SS304L의 극저온 및 상온용 고성능 부품 제조를 위한 LPBF 공정 변수 최적화에 관한 핵심적인 지침을 제공한다.

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내화 원소 Mo을 활용한 고강도 면심입방구조 다원계 합금 개발

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Novel CoNiMo-based complex-concentrated alloys with exceptional strength-ductility synergy

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ABSTRACT

In recent years, the concept of complex-concentrated alloys (CCAs), defined by their multicomponent solid solution, has enabled the development of advanced structural materials with outstanding mechanical properties. Among these, single face-centered-cubic (FCC) CCAs have attracted considerable interest as a matrix material for advanced structural applications due to their remarkable strength-ductility combination. However, the design of such alloys typically relies on combinations of 3d transition metals, as even minor additions of non-3d elements often induce the formation of brittle intermetallics, leading to a limitation of compositional flexibility.

To overcome this constraint, we have developed a novel CoNiMo system that retains a single FCC solid solution while incorporating significant amounts of Mo. The addition of Mo simultaneously enhances solid-solution strengthening, grain-boundary strengthening, and strain-hardening capacity, leading to a remarkable combination of tensile strength exceeding 1.3 GPa and ductility approaching 50%. Theoretical calculations reveal the promising effect of Mo in terms of lattice distortion and stacking fault energy, both of which play key roles in strengthening and plastic deformation mechanisms. Atom probe tomography further confirms Mo segregation at grain boundaries, contributing to improved grain-boundary strengthening.

Despite maintaining a stable FCC phase, the single-phase CoNiMo alloy system

exhibits moderate yield strength, motivating the implementation of additional strengthening strategies. Therefore, we employ two strengthening strategies: (1) implementation of ultra-fine grain via severe plastic deformation followed by short-time annealing and (2) precipitation strengthening through coherent nanoscale precipitates. Through systematic alloy design, the correlation between microstructure and mechanical properties of these CoNiMo-based CCAs is investigated, achieving an ultra-high strength and sufficient ductility. The successful development of ultra-strong, ductile CoNiMo-based CCAs highlights the potential of extending compositional design space and mechanical property ranges in FCC-structured CCAs.

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Laser powder bed fusion 공정 및 탄소 첨가 효과를 통한 NiCoCr 합금의 극저온에서 고온 강도 향상

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Enhanced Cryogenic-to-High-Temperature Strength of NiCoCr Alloys via Laser Powder Bed Fusion and Carbon Alloying

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ABSTRACT

최근 고온 내산화성 및 극저온 인성을 동시에 갖춘 고성능 구조재료에 대한 수요가 증가함에 따라, Cantor 합금계에서 파생된 NiCoCr 중엔트로피 합금(MEA)이 차세대 극한환경용 소재로 주목받고 있다. 본 연구에서는 탄소를 사전 합금화한 $(NiCoCr)_{99.25}C_{0.75}$ (at.%) MEA 분말을 사용하여 laser powder bed fusion (LPBF) 공정으로 시편을 제작하고, 석출 강화 열처리를 수행하여 극저온부터 고온까지의 기계적 특성과 변형 기구를 체계적으로 규명하였다.

LPBF 공정을 통해 제조된 합금은 99.9% 이상의 상대밀도와 columnar 결정립 구조, 그리고 결정립 내부에 substructure를 형성하였다. 후열처리(700 °C, 1시간, 수냉)를 통해 Cr이 풍부한 탄화물($Cr_{23}C_6$)이 결정립 및 substructure 경계에 석출되었으며, 이는 전위 이동과 grain boundary migration을 억제하는 Zener pinning 효과를 유도하였다. 또한 열처리는 NiCoCr FCC matrix에 고용된 침입형 원소 (C, O)를 소비시켜 matrix의 stacking fault energy를 감소시키는 효과를 부여했다.

기계적 특성 평가 결과, 극저온(77 K) 인장 시험에서 항복강도 1.23 GPa, 인장강도 1.60 GPa를 달성하였고, 이는 기존 LPBF 기반 NiCoCr 계 합금 대비 우수한 성능이다. 극저온 변형 시, deformation twinning (DT), stacking fault (SF), 그리고 석출물-전위 상호작용에 기인한 전위 구속 효과가 관찰되었으며, 이로 인해 높은 가공 경화율과 동적 Hall-Petch 효과가 유도되었다.

또한, 25 - 800 °C 범위의 압축 시험 결과, 본 합금은 700 °C까지 항복강도의 완만한 감소(약 0.387 MPa/°C)를 보이며, 800 °C에서도 432 MPa의 항복강도를 유지하였다. 이는 고온에서도 전위 집적, Orowan 강화, hetero deformation induced hardening (HDI

hardening) 효과가 유효하게 작용했음을 시사한다. 특히, 고온 변형 시 발생한 dynamic recrystallization은 나노 석출물에 의한 결정립계 이동 억제로 지연되었으며, DRX된 결정립 내에서도 stacking fault와 deformation twin이 관찰되어 강화 인자의 역할을 유지하였다.

본 연구는 탄소 첨가 및 LPBF 공정 기반의 미세조직 제어 전략을 통해 극한 온도 범위에서 우수한 기계적 특성을 갖는 NiCoCr 기반 합금의 가능성을 제시하였으며, 향후 극저온 및 고온용 금속 구조재료 설계에 실질적 기여를 할 수 있음을 입증하였다.

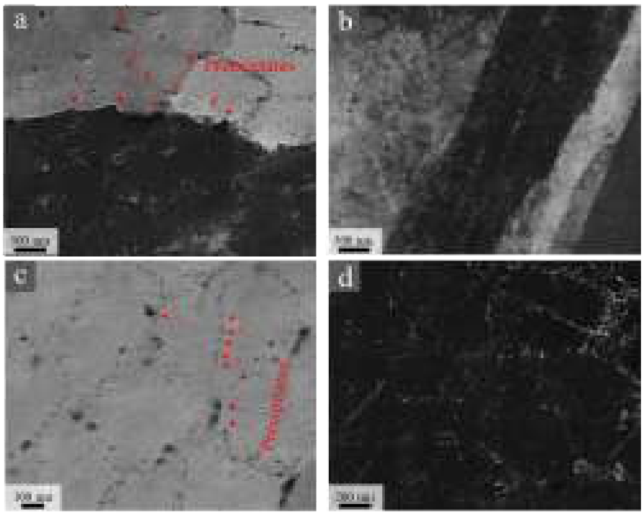

Fig. 1 Microstucture of heat-treated LPBF-built $(NiCoCr)_{99.25}C_{0.75}$ MEA: (a) BSE and ECC mixed mode image by different grains, (b) ECC image showing columnar substructures, and (c) BSE image and (d) ECC image of sub-cell decorated with dislocations and nano-precipitates.

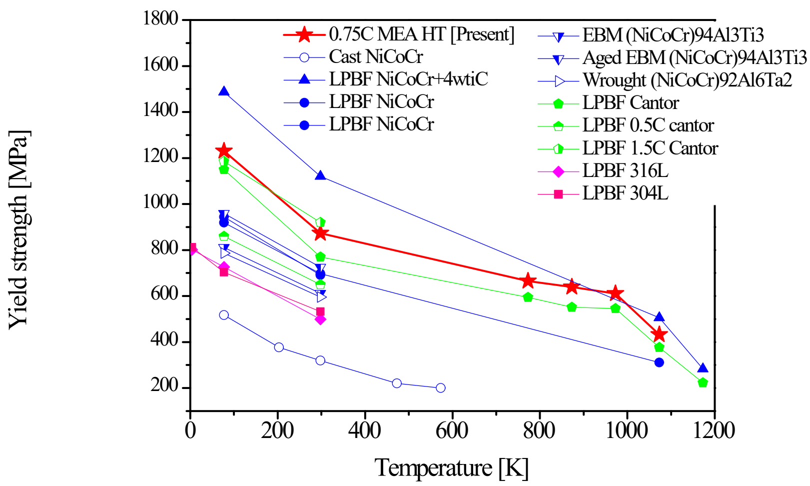

Fig. 2 Temperature-dependent yield strength of the heat-treated LPBF-built $(NiCoCr)_{99.25}C_{0.75}$ MEA (this study) compared with various reported NiCoCr-based alloys and conventional structural materials. The present alloy demonstrates superior strength retention across a wide temperature range (77 - 1073 K), exceeding that of cast and wrought NiCoCr alloys, LPBF Cantor and commercial stainless steels.

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Co37-Cr20-Mn15-Ni14-Fe14 고엔트로피 합금의 변형쌍정 기구

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Deformation twin mechanism of Co37-Cr20-Mn15-Ni14-Fe14 high entropy alloy

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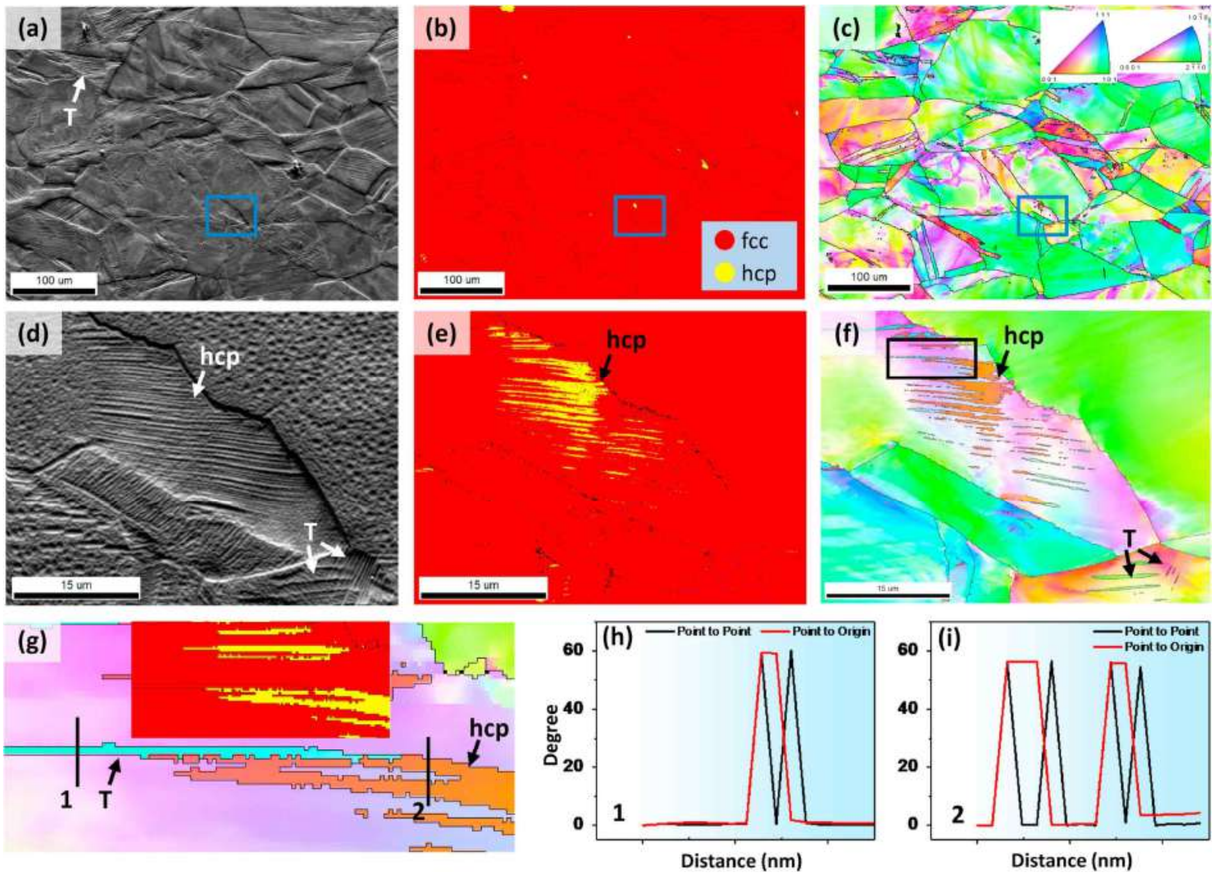
ABSTRACT

The microstructural evolution of a Co-based high-entropy alloy (HEA) was examined using electron microscopies, confirming the prominent presence of stacking faults (SFs) and deformation twins during compression. A novel twinning mechanism involving a local fcc → hcp transformation at the medium deformation stage was discovered, which had not been hitherto reported in HEAs. High-resolution scanning transmission electron microscopy revealed the conversion of a pre-twinned ε-martensite-like phase, featuring a local hcp structure, into a stable three-layer twin lamella through the nucleation of new SFs in between pre-existing ones. Additionally, as deformation progressed, the Niewzcas and Saada's pole mechanism of twinning

was simultaneously activated, resulting in the formation of nano-twins within the HEA structure at higher deformation stages. The activation of both twinning mechanisms was analyzed by considering the concept of effective stacking fault energy, and stacking fault and twin fault probabilities, calculated through X-ray diffraction analysis at each deformation stage. Finally, the activation energy associated with dislocation-SFs and twin boundary interactions, as well as their respective influences on the strain-hardening behavior of the HEA at each deformation stage, were thoroughly investigated using thermally activated parameters obtained from cyclic stress relaxation experiments.



(a) Microstructural analysis at the true strain of 0.25: (a): FSD image showing the formation of dense SFs inside most of the grains. The bands indicated by the white arrow are deformation twins, (indicated by “T”s; please see the supplementary document for more details). (b) and (c): Phase and IPF maps of (a), respectively, with a step size of 400 nm. (d), (e), and (f): Higher magnification from the regions inside the rectangular in (a), (b), and (c), respectively, with the step size of 40 nm, showing deformation twins and hcp lamellae. (g): Higher magnification of the region inside the rectangular in (f) including its inserted phase map, showing a hcp lamella converting into a twin lamella. (h) and (i): Line scans from the lines labeled as "1" and "2", respectively.

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나프타 크래킹 공정용 Ni기 초합금 강관재의 표면 산화물이 내부 침탄 거동 및 기계적 강도에 미치는 영향 고찰

김응룡[1,2], 이영국[2], 김동익[1]
1. 한국과학기술연구원 수소에너지소재연구단
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The investigation into the carburization and related mechanical behaviors in Ni base superalloy tube materials for Naptha cracking process

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2. Department of Materials Science and Engineering, Yonsei University, Seoul, 03722, Korea

ABSTRACT

In the petrochemical industry, Ethylene is an important material as a block unit and it is produced by the thermal cracking process that decompose high-weight hydrocarbons such as Naphtha into low-weight hydrocarbons by heating at high temperature and reducing atmosphere in the gas tube. For enduring process, it is necessary to develop a gas tube with excellent corrosion resistance.
Recently, the gas tube composed alumina forming alloy was developed in which 2 to 4% of aluminum was added in a Cr-Ni alloy. An aluminum oxide layer is known to be more stable under high temperature and water vapor conditions than chromium oxide.
To ensure the high temperature corrosion resistance of alumina forming alloy comparing with the conventional chromia forming alloy, the thermo-chemical treatment simulating cyclic thermal cracking process were performed in both alloys and investigated internal phase evolution and mechanical property variations according to the treatment. The comparative behavior of the two alloys were predicted with computational thermodynamics calculation such as Thermo-calc and Fact-Sage and

M_3C_2, M_7C_3, $M_{23}C_6$ were suggested as stable phases. Then the processed cross-section specimens were analyzed using EBSD and EPMA for investigation of inner phase. In actual analysis, chromia forming alloy was formed the M_3C_2, M_7C_3 and $M_{23}C_6$. On the other hand, the internal carbide of the alumina forming alloy showed few carbides inside.

At coking process, the chromia layer which role protective film was transformed into carbide to reduction reaction from hydrogen and carbon penetrate the matrix. Additionaly, a thick coke layer over 20 μm was formed and thick coke layer was invigorated to catalyst reaction during reducing chromium oxide to chromium carbide. On the other hand, the alumina layer was stable, and the surface coke layer was just 1 – 2 μm.

The mechanical properties from the carbide formed therein affects were measured that the chromium forming alloy had a high hardness, but had a brittle characteristics, whereas the alumina forming alloy with a high internal carburization resistance showed a ductile characteristics.

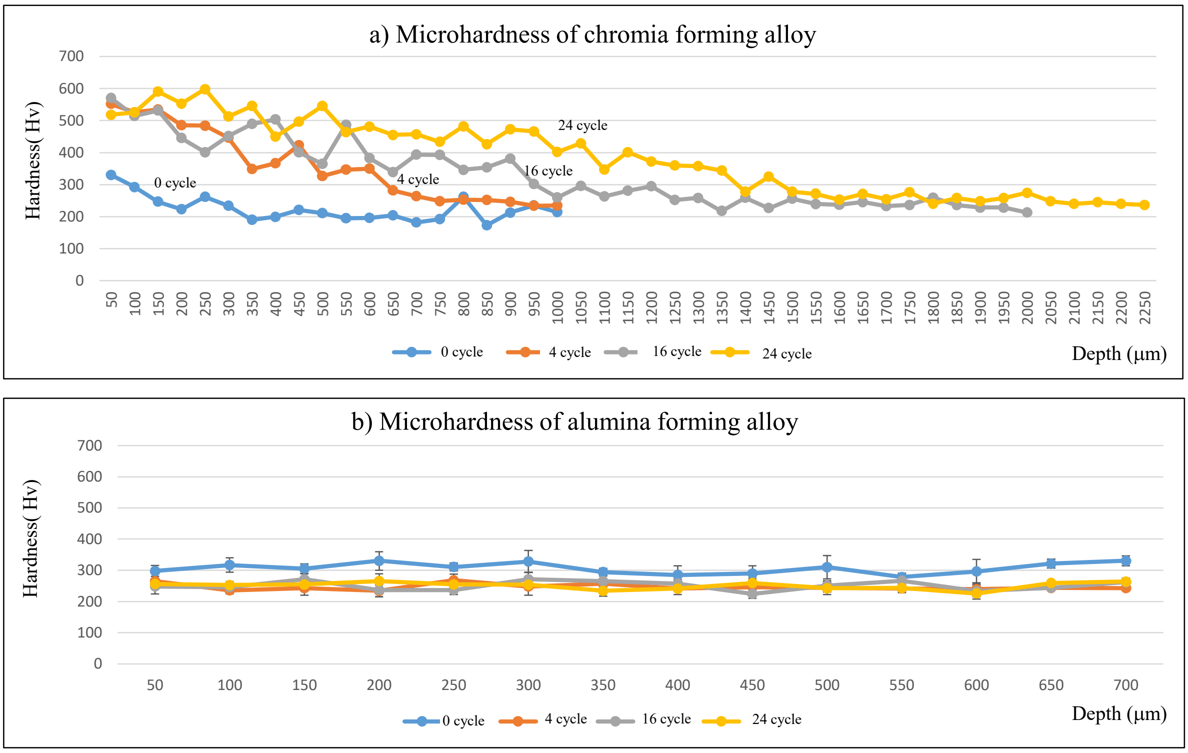

Fig. Mechanical property variations according to the carburization in a) chromia forming and b) alumina forming Nickel base superalloys.

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3차원 원자단층현미경을 활용한 금속재료의 원자단위 화학 조성 분석

정찬원
부경대학교 재료공학전공, 부산광역시 남구 용소로 45 대한민국
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Atomic-scale three-dimensional elemental distribution analysis of metallic materials using atom probe tomography

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ABSTRACT

The properties of materials are strongly influenced by their microstructure, making it essential to understand microstructural features in detail. These features span a wide range of length scales—from the atomic level to the microscale—necessitating a comprehensive, multi-scale approach to microstructural characterization. Among these, nanoscale analysis is particularly challenging due to the limited signal and extremely small dimensions, yet it is critical for uncovering the origins of materials' unique properties and behaviors. For instance, grain boundary segregation can affect intergranular cohesion, resulting in impact toughness, nanoscale chemical inhomogeneities can modify dislocation motion, and interfaces between nanoprecipitates and the matrix can improve mechanical strength. In this context, atom probe tomography (APT) serves as a powerful analytical tool, enabling three-dimensional (3D) reconstruction of atomic-scale chemical distributions with sub-nanometer spatial resolution and chemical sensitivity down to the parts-per-million (ppm) level. APT has been widely applied to visualize 3D elemental distributions in a range of materials—including metals, semiconductors, and even biomaterials—to clarify the relationship between structure and properties. In this talk, I will briefly introduce the fundamental principles of APT and share selected examples of its application in the analysis of metallic materials.

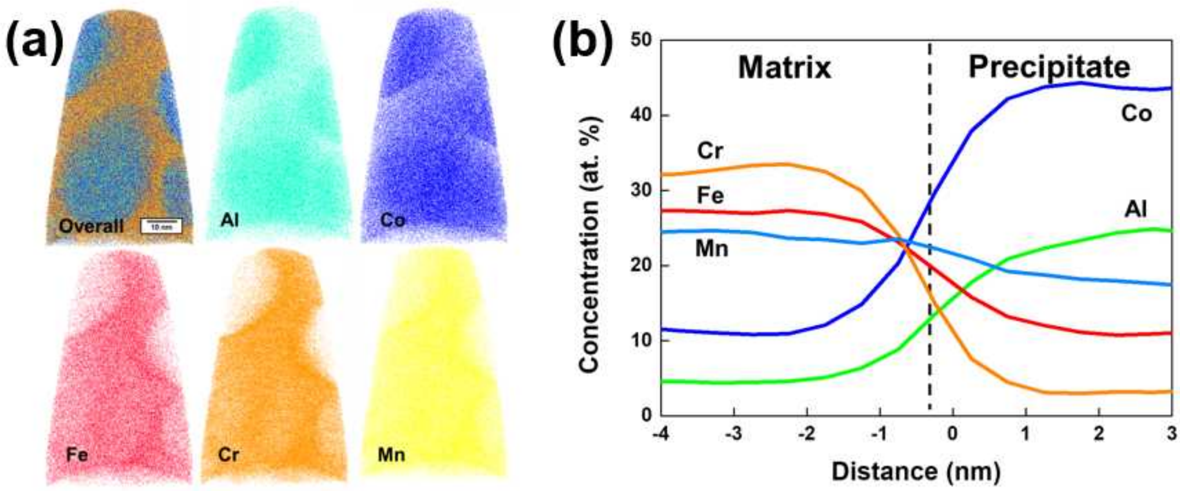

Figure 52. (a) 3D atom maps of $Al_{0.1}(FeCoCrMn)_{0.9}$ alloy and (b) proximity histrogram across the nanoprecipitates.

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CrMnFeCoNi 고엔트로피 합금의 형상기억특성에 미치는 결정립 크기의 영향

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Effect of grain size on shape memory effect in CrMnFeCoNi alloys

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ABSTRACT

The concept of high-entropy alloy (HEA) design has generated significant interest for the exploration of vast composition space offered by multi-principal elements. An equiatomic CrMnFeCoNi alloy, with a simple FCC crystal structure, is one of the most significantly investigated single-phase HEAs. This alloy showed excellent tensile properties and fracture toughness at cryogenic temperatures due to deformation-induced nano-twinning, which is favored in materials with low stacking fault energy. Here, we investigated the effect of the grain size on the recovery strain of a non-equiatomic FCC CrMnFeCoNi HEA. A series of $Cr_{20}Mn_{20}Fe_{20}Co_{35}Ni_5$ (Ni5) HEAs with grain sizes ranging from 14 to 730 μm were produced by varying casting, rolling, and annealing conditions. As the grain size increased, the density of grain and twin boundaries decreased, while the volume fraction of stress-induced HCP martensite increased from 5 to 31 %. The cast-and-annealed Ni5 HEA with a maximum grain size of 730 μm exhibited a peak recovery strain of 4.7 % under tensile pre-straining followed by recovery heating. This is attributed to the low strain-hardening rate and high critical strain for plastic yielding, indicating that stress-induced martensitic transformation is the dominant deformation mode at the early stage of plastic deformation.

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분말 재사용 LPBF 공정에 의한 Ni기 초내열합금의 In-situ 산화물 분산 강화

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In-situ Oxide Dispersion Strengthening of Ni-base Superalloy via Powder Reuse in Laser Powder Bed Fusion

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ABSTRACT

Additive manufacturing (AM) via laser powder bed fusion (LPBF) has attracted significant attention for its potential to reduce raw material consumption, energy use, and overall manufacturing costs, while enabling unprecedented design freedom and the production of complex geometries. Given the high cost of metal powders, powder reuse is essential for the economic and sustainable implementation of LPBF; however, repeated reuse can change powder morphology, particle size distribution, and chemical composition, potentially influencing the resulting microstructure and mechanical properties of fabricated parts. In this study, IN718 powder was reused up to ten times using a virgin powder supplementation method to maintain a constant feedstock volume while minimizing quality degradation. Reuse increased the average powder particle size (d50) from 35 to 39.9 μm and led to oxidation, resulting in alumina spot formation (~1–2 μm) on the powder surface. Consequently, fine alumina particles (<100 nm) were formed in the austenitic matrix of the fabricated parts, altering their recrystallization behavior during homogenization heat treatment at 1065 °C. The recrystallization fraction decreased from 89.6% to 82.7% with increasing reuse iterations due to enhanced Smith–Zener pinning by alumina particles, while unrecrystallized grains retained higher dislocation densities. These microstructural changes promoted planar dislocation gliding (Taylor lattice formation) as the dominant

deformation mechanism during tensile loading, resulting in an unusual combination of increased yield and ultimate tensile strengths and maintained or slightly improved ductility at both 25 °C and 650 °C. The results demonstrate that controlled powder reuse not only supports sustainability and cost reduction but also introduces a beneficial in-situ oxide dispersion strengthening (ODS) effect. However, the study suggests a potential threshold for this ODS effect, emphasizing the importance of establishing reuse criteria and evaluating long-term properties such as creep and fatigue for broader industrial applications of LPBF-fabricated IN718 components.

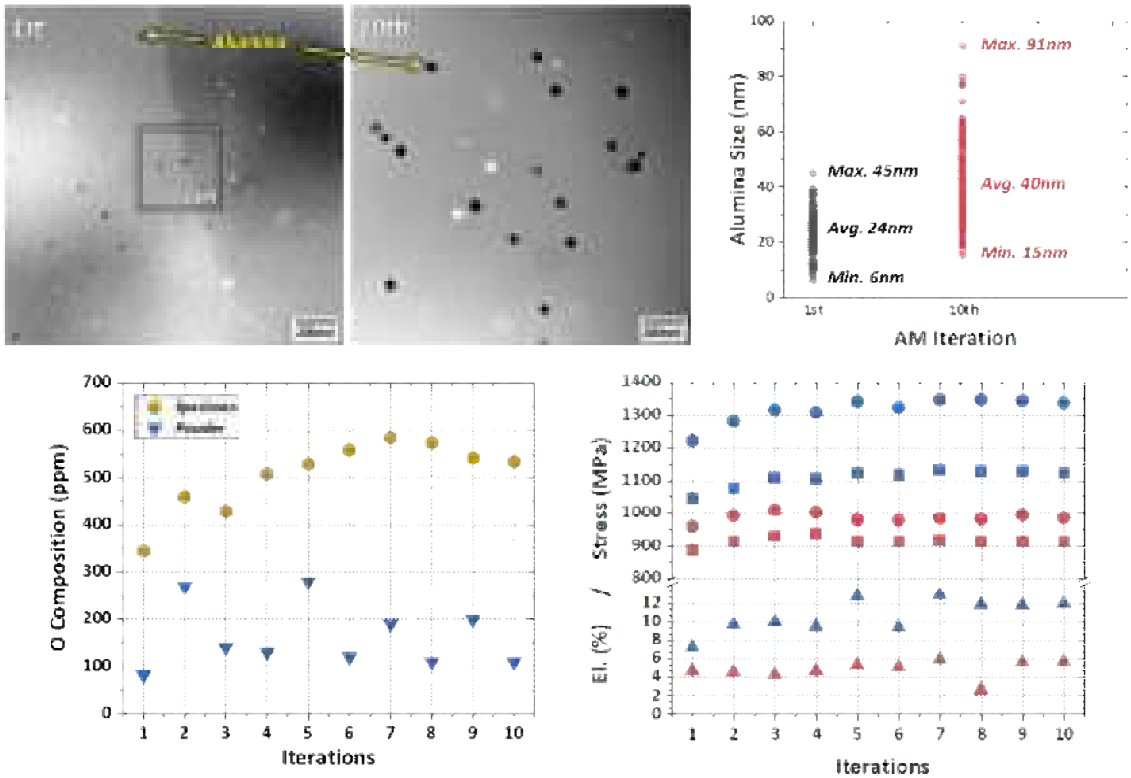

Figure. STEM HAADF images showing alumina distributions as dark spots in the 1st and 10th specimens, along with a comparison of alumina particle sizes between the two conditions. The variation in oxygen composition of both the reused powder and the SLMed specimens is presented as a function of iteration number. Additionally, the tensile properties, including yield stress (square), ultimate tensile strength (circle), and elongation (triangle) measured at 25°C (blue) and 650°C (red), are plotted to illustrate the influence of powder reuse on mechanical performance.

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점진액상소결 공정에 의한 고체/액체 계면 제어 기반 동적 치밀화 최적화에 관한 연구

이연주[1*], 설재복[1], 조기섭[1], 성효경[1], 권도훈[2], 김휘준[2], 최현주[1]
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A Study on the Optimization of Dynamic Densification based on solid/liquid interface control via Progressive Liquid Sintering

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ABSTRACT

Powder metal compacts offer high dimensional accuracy and material utilization efficiency in powder metallurgy-based manufacturing processes. However, pores inevitably form during compaction and sintering, resulting in reduced density and deterioration of mechanical, electrical, and corrosion properties. In particular, under high-temperature conditions, even micro-scale pores act as stress concentrators, significantly degrading creep resistance and other high-temperature mechanical properties. To address these issues, various pore elimination methods have been developed. Among them, liquid phase sintering (LPS) at elevated temperatures is advantageous over solid-state sintering in terms of densification. However, conventional LPS requires full liquefaction of the material and prolonged high-temperature exposure, leading to increased processing costs and risks of

distortion.

This study proposes a dynamic densification approach to overcome the limitations of conventional methods by employing progressive liquid sintering (PLS), in which the solid/liquid coexistence region is gradually advanced to remove internal pores. In this process, the moving solid/liquid interface facilitates pore migration through differences in gas solubility and enhanced diffusion-driven transport, enabling more effective and economical densification. Experiments were conducted on Cr-30wt.%Ni alloy under varying PLS conditions (e.g., temperature, interface movement speed) to analyze pore distribution, porosity, and high-temperature mechanical properties. Additionally, compositional uniformity was maintained throughout the dynamic sintering process, as confirmed by post-sintering analysis (steady densification). The results clearly demonstrate the active removal of pores and significant improvement in high-temperature mechanical performance due to the controlled movement of the solid/liquid interface. This study presents a practical and cost-effective processing strategy for enhancing the properties of next-generation high-temperature structural materials.

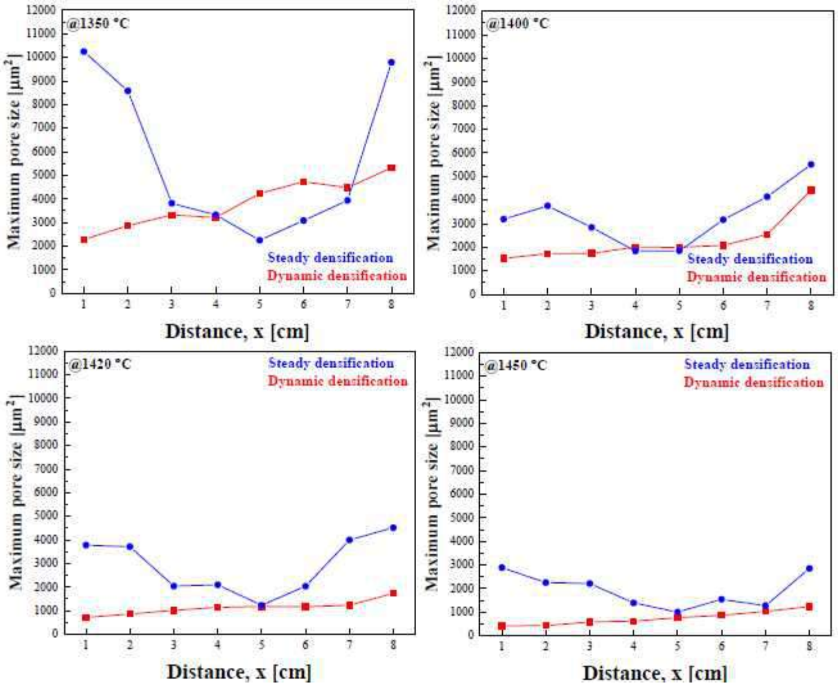

Figure 1. Distribution of pore volume fraction at different locations under each densification condition

소재혁신선도본부

임무와 역할

소재혁신선도본부 본부장 | 이상관

임무

소재 대외의존도 해소, **소부장 미래 경쟁력 확보** 및 생태계 강화를 위한 **소재혁신선도 플랫폼 구축**

- 과기부 소부장 관련 정책수립 밀착 지원
- 미래선도품목 중심의 기술난제 극복지원 (미래기술연구실 100개)
- 소재자립화 품목의 미래지향적 기술자립화 지원 (국가핵심소재연구단 100개)
- 소부장 R&D 커뮤니티 활성화 (소부장 전문가협의체)

주요업무

소재·부품 핵심기술 조기 확보를 위한 R&D 정책 수립
과기부 소부장 관련 정책 수립 및 지원

소부장 관련 신규사업 발굴 및 R&D 기획
국가핵심소재, 미래소재 등 신규 R&D기획

과기부 소재 연구단 성과관리 및 지원
원천특허 확보, 기술이전, 성과홍보, 연계방안 도출 등 연구단 맞춤형 지원 (국가핵심소재연구단, 미래기술연구실)

소부장 산·학·연 협력네트워크 구축 및 운영
전문가협의회 운영 (12대 국가전략기술분야 25개 전문연구회), 소재연구기관협의회 운영

신규 R&D 발굴 및 기획 추진

미래소재 R&D (전략형) " 국가전략기술기반 미래소재 발굴 지원 "

미래기술 연구실 확대 ▶ 차세대 유망 미래소재 선점 • 전략형소재 과제 : 21개 연구실('22.12) → 100개 확대 운영('25년)

| 차세대 주력산업 및 기술패러다임 변화를 주도하고 미래 소부장을 선점할 수 있는 '미래소재' 확보 추진

- 국가전략기술을 뒷받침할 수 있는 기술난제 극복 지원을 위한 "전략형" 과제 신규 기획
  - [현황] '21년 4개 전략형 시범사업 추진 / '22년 17개 전략형 과제 본격 추진

국가핵심소재 R&D (플랫폼형/특화형) " 소부장 핵심품목의 미래지향적 기술자립 지원 "

국가핵심소재연구단 확대 ▶ 소부장 R&D핵심품목 기술자립 + 공급망 대체 • 69개 연구단('22.12) → 100개 연구단 확대('25)

| 소재 부품 장비 R&D핵심품목 기술 및 미래선도 품목과 연계, 다양한 품목의 기술 자립을 위한 핵심기술 조기 확보 추진

- 플랫폼형(5년) : 소재혁신선도 프로젝트, 공백 품목(중점요소), 징검다리기 / 특화형 (3년) : 단일품목 핵심기술
  - [현황] '21년 57개 연구단 운영 / '22년 12개 연구단 추가 운영

소재전문연구회

소재전문연구회 구성 및 운영 " 국가전략기술분야별 25개 전문연구회 "

| 구성현황 : 12대 분야(12대 국가전략기술 + 융합) 25개 소재 전문연구회 / 산학연 전문가로 약 350여명으로 구성

| 활동현황 : 미래소재 발굴 및 전략기술로드맵 마련을 위해 총 100회 이상의 적극적인 연구회 활동 수행

반도체
1. 미래반도체 연구회
2. 특화반도체 연구회
3. 첨단패키징 연구회

디스플레이
1. 자유형상디스플레이 연구회
2. 초실감디스플레이 연구회
3. 친환경디스플레이 연구회

차세대원자력
1. 차세대원전소재 연구회
2. 핵융합소재 연구회

첨단 모빌리티
1. 스마트모빌리티소재 연구회
2. 친환경모빌리티소재 연구회

이차전지
1. 이차전지소재 연구회

수소
1. 수소에너지 연구회
2. 연료전지 연구회

첨단바이오
1. 생체소재 연구회
2. 헬스케어소재 연구회

우주·항공
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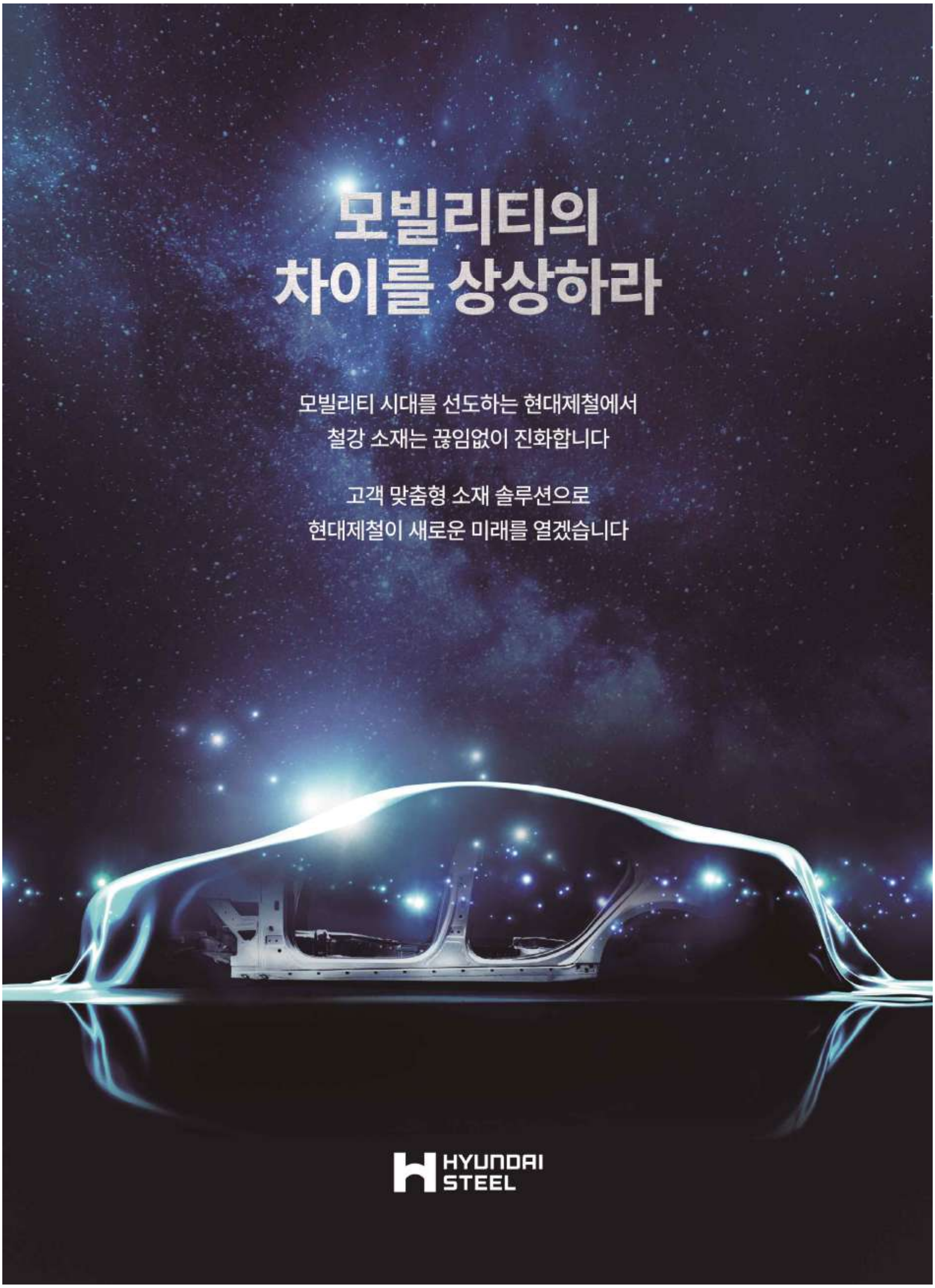
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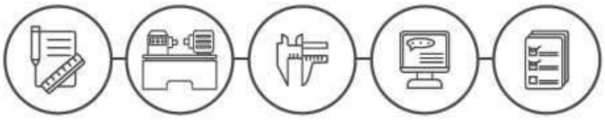

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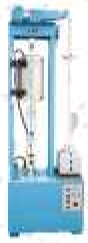

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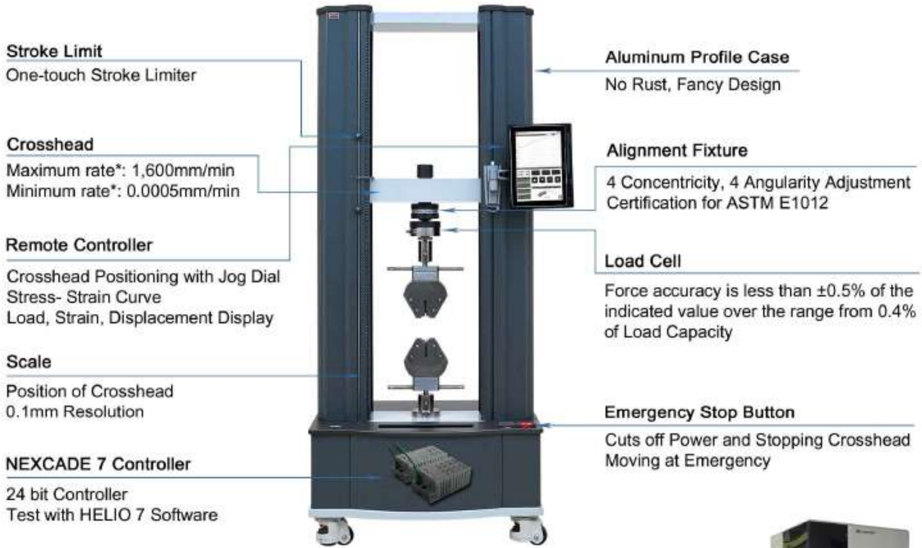

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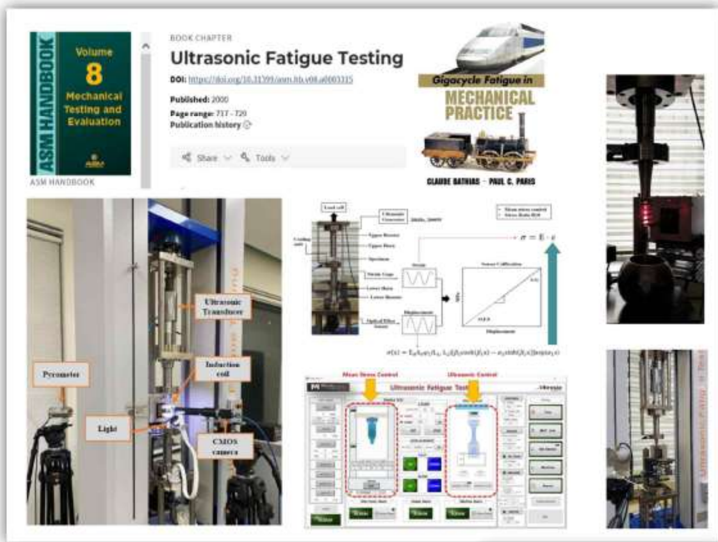
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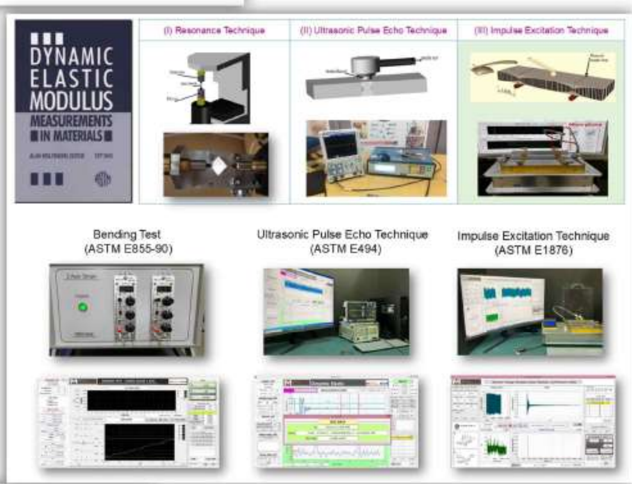
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