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ABSTRACT

Keywords:
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The LTSR condition was designed based on differential scanning calorimetry (DSC) analysis to suppress excessive thermal exposure during stress relief and modify the subsequent precipitation pathway. Compared with the conventional HTSR route, the proposed LTSR strategy preserved a larger fraction of the build-induced interdendritic Laves network, resulting in a distinctly different precipitation evolution after the standard heat treatment. Under the HTSR route, rapid Laves dissolution caused localized coarse δ precipitation. In contrast, the LTSR route preserved the interdendritic Laves network, maintained tensile properties and engineering microstructure, producing finer, more uniformly distributed precipitates. EBSD and TEM analyses revealed lower kernel average misorientation (KAM) and more homogeneous precipitation behavior. The retained network is considered to influence the subsequent precipitation pathway through delayed Nb redistribution, although direct quantification of Nb redistribution was beyond the scope of the present study. Tensile tests demonstrated that the LTSR-treated condition exhibits a modest increase in ultimate tensile strength, while a slight reduction in elevated-temperature yield strength and ductility is observed at 649 °C. These findings demonstrate that the LTSR strategy provides an alternative post-processing route for controlling precipitation evolution through modification of the remaining interdendritic microstructure, offering a new approach for tailoring the microstructure of LPBF-fabricated Inconel 718.

Additive manufacturing (AM) technology has attracted continuous attention in the aerospace and high-performance structural material fields owing to its superior geometric design freedom, high material utilization efficiency, and process integration capability [1–3]. In

particular, Inconel 718 fabricated by laser powder bed fusion (LPBF) has been extensively investigated for aerospace and high-temperature structural applications because it can simultaneously provide excellent high-temperature strength, corrosion resistance, and complex-shape manufacturability [4–6]. However, due to the rapid melting and solidification characteristics of the LPBF process, non-equilibrium

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microstructures distinct from those of conventional cast or wrought materials are formed, including cellular substructures, residual stresses, elemental segregation, and interdendritic Nb-rich Laves phase formation [7–9].

In LPBF-fabricated Inconel 718, Nb segregation preferentially occurs in interdendritic regions during rapid solidification, leading to the formation of residual Laves networks. Such non-equilibrium microstructures are known to significantly influence subsequent microstructural evolution and mechanical property changes during post heat treatment [10–12]. In general, the Laves phase has been regarded as a brittle phase that induces local Nb depletion and suppresses the formation of γ' strengthening precipitates; therefore, it has conventionally been considered a phase that should be removed or minimized [13–15]. Accordingly, most previous studies have focused on eliminating residual segregation and Laves phases through homogenization-based heat treatment or high-temperature post-processing approaches [16–18].

To relieve residual stresses and improve microstructural stability in LPBF-fabricated Inconel 718, various post-processing treatments such as stress relief (SR), solution heat treatment (SHT), and aging treatment have been widely applied [19–21]. Among them, high-temperature stress relief (HTSR) has been extensively utilized because the rapid diffusion behavior at elevated temperatures effectively promotes residual stress relaxation and partial homogenization while accelerating the breakdown of residual Laves phases [22–24]. However, excessive thermal exposure may cause rapid collapse of the residual Laves network, subsequently promoting localized grain-boundary δ precipitation during aging treatment, which can affect strengthening phase stability and final mechanical properties [25–27].

Recently, increasing attention has been directed not only toward the removal of Laves phases but also toward precipitation behavior and phase evolution occurring during post-processing of LPBF-fabricated Inconel 718 [28,29]. In particular, thermal exposure conditions during the stress-relief stage can directly affect residual microstructure stability and subsequent precipitation pathways, potentially leading to changes in the morphology and distribution of δ phases during subsequent aging treatment [30]. Nevertheless, most previous studies have primarily focused on high-temperature homogenization or hot isostatic pressing (HIP)-based approaches, while studies investigating the relationship between stress-relief temperature, residual Laves morphology, and precipitation evolution remain relatively limited.

Although these studies have provided valuable insights into homogenization behavior and precipitation evolution, they have generally regarded the Laves phase as a detrimental constituent that should be eliminated through high-temperature post-processing. Consequently, relatively little attention has been paid to how partial retention of the interdendritic Laves network prior to standard heat treatment influences the subsequent precipitation pathway and mechanical properties. Moreover, the independent role of the stress-relief strategy in governing residual microstructural stability before solution treatment and aging has not yet been systematically investigated.

From this perspective, low-temperature stress relief (LTSR) may provide an alternative strategy capable of suppressing excessive thermal exposure while partially retaining the interdendritic Laves network. Specifically, changes in the stability of the residual Laves network are expected to be closely related to subsequent precipitation behavior during aging treatment, which may ultimately influence the final mechanical properties.

Based on this background, the objective of the present study is to systematically investigate the influence of stress-relief temperature on the evolution of the retained interdendritic Laves network and the subsequent precipitation pathway in LPBF-fabricated Inconel 718 by comparing the conventional high-temperature stress-relief (HTSR) strategy with the proposed low-temperature stress-relief (LTSR) strategy. Particular emphasis is placed on clarifying how the stress-relief strategy influences the subsequent precipitation behavior and the resulting mechanical properties. Furthermore, changes in the stability of

the remaining Laves morphology are expected to influence the subsequent precipitation pathway, although the underlying Nb redistribution mechanism has not yet been directly quantified in the present study.

2. Experimental method

2.1. Powder characteristics and LPBF-fabricated Inconel 718 specimens

Gas-atomized Inconel 718 powder (Tekna Inc., Canada) was used for LPBF fabrication in the present study. Table 1 summarizes the AMS 5662 N compositional specification range for additive-manufacturing-grade Inconel 718 together with the actual chemical composition of the Tekna powder used in this work. The powder composition satisfied the AMS 5662 N specification range in terms of C, Cr, Mo, Nb, Ti, and Al contents, indicating its suitability as a Ni-based superalloy powder for LPBF processing. In particular, the Nb content of the powder was measured to be approximately 5.24 wt%, which is considered a critical element directly influencing interdendritic Nb segregation and residual Laves phase formation during the LPBF process.

Powder morphology was characterized using a field-emission scanning electron microscope (FE-SEM; HITACHI SU8600), while the particle size distribution was measured using a particle size analyzer (Malvern, Mastersizer 3000E). Fig. 1(a) shows the morphology of the IN718 powder used in this study. Most powder particles exhibit a highly spherical morphology with high sphericity. Although a small number of satellite particles were observed, the overall powder morphology was relatively uniform, which is considered beneficial for stable powder spreading and melt behavior during LPBF processing.

Fig. 1(b) presents the particle size distribution of the powder. The measured D_{10} , D_{50} , and D_{90} values were 23.64 μm , 32.61 μm , and 46.98 μm , respectively, with an estimated statistical deviation of approximately $\pm 9.2 \mu\text{m}$. The powder exhibited a primary particle size distribution within the range of approximately 20–50 μm , together with a relatively narrow particle size distribution. This particle size range is generally considered suitable for LPBF processing of Ni-based superalloys because it promotes uniform layer deposition and stable energy transfer during fabrication.

The thermophysical properties and optical absorption characteristics of the Inconel 718 powder are presented in Fig. 1(c and d). The powder density was measured to be 8.19 g/cm^3 , and the melting temperature was approximately 1260 $^{\circ}\text{C}$. In addition, the specific heat capacity and heat of fusion were calculated to be 0.435 $\text{J}/\text{g}\cdot^{\circ}\text{C}$ and 16.94 kJ/mol , respectively. Fig. 1(d) shows the absorptivity of the powder as a function of laser wavelength. At the fiber-laser wavelength commonly used for LPBF processing (1080 nm), the powder exhibited an absorptivity of approximately 0.596, indicating relatively stable laser energy absorption behavior.

The LPBF specimens were fabricated using the above-mentioned IN718 powder under an Ar atmosphere. To achieve sufficient relative density, commercial processing parameters provided by EOS for Ni-based superalloys were adopted. Fabrication was carried out using an EOS LPBF system under the following conditions: laser power of 285 W, scan speed of 960 mm/s, hatch spacing of 100 μm , and layer thickness of 40 μm [31]. In addition, a stripe scanning strategy was employed during fabrication.

Since the primary objective of this study was to investigate the stability of residual Laves networks and subsequent precipitation behavior according to different stress-relief conditions, all specimens were fabricated using identical LPBF processing parameters. The fabricated specimens were subsequently subjected to stress-relief, solution heat treatment, and aging treatment processes for further characterization.

2.2. Heat-treatment strategy and specimen classification

The specimens were classified according to the applied heat-treatment conditions. The LPBF-fabricated condition without post-

Table 1
Chemical compositions of Inconel 718 powder (wt. %).

Component	C	Mn	Si	P	S	Cr	Co	Mo	Nb	Ti	Al	Fe	Cu	Ni	B
TEKNA (in study)	0.02	0.0017	0.028	-	0.005	19.8	-	3.23	5.24	0.737	0.684	Re main	0.0285	54.9	-

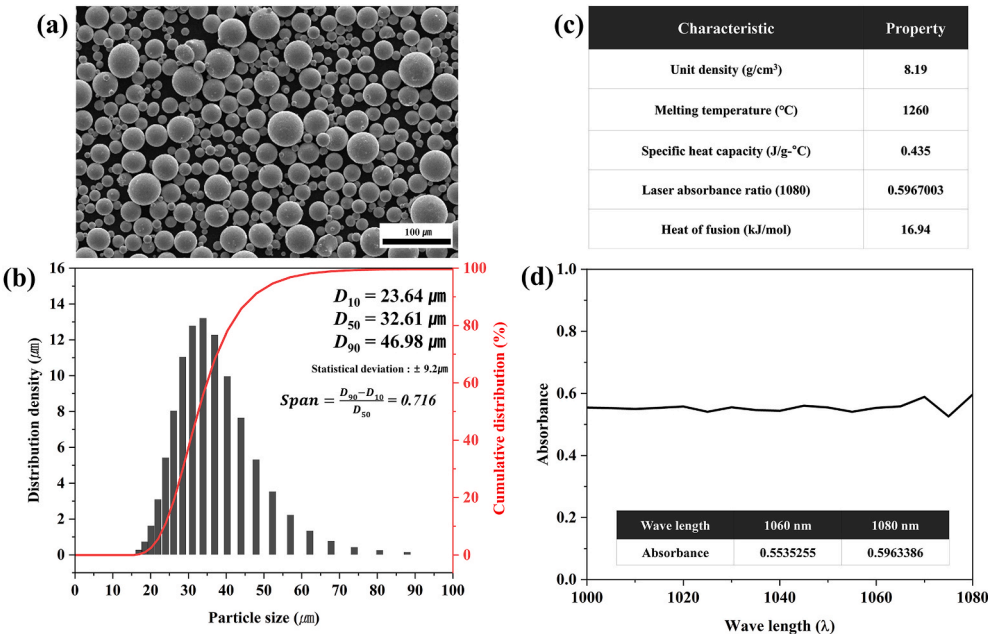


Fig. 1. Characteristics of the IN718 powder used for LPBF fabrication: (a) SEM image showing powder morphology, (b) particle size distribution, (c) thermophysical properties of the powder, and (d) absorptivity and estimated energy density according to laser wavelength.

processing was designated as the As-built condition, while specimens subjected to high-temperature stress relief and low-temperature stress relief were denoted as HTSR and LTSR, respectively. In addition, specimens subjected to solution heat treatment and aging treatment after HTSR were designated as HTST (high-temperature stress-relief followed by standard treatment), whereas specimens subjected to identical post-heat-treatment procedures after LTSR were designated as LTST (low-temperature stress-relief followed by standard treatment).

A schematic illustration of the stress-relief and subsequent heat-treatment routes employed in this study is presented in Fig. 2. For clarity, the four post-processing conditions investigated in the present study (HTSR, LTSR, HTST, and LTST) are summarized in Table 2, together with the corresponding stress-relief, solution treatment, and aging schedules. To investigate the influence of stress-relief temperature

on microstructural evolution and mechanical properties, both HTSR and LTSR conditions were applied.

The HTSR condition was established based on the stress-relief condition recommended in ASTM F3055 for LPBF-fabricated Inconel 718. Therefore, the HTSR treatment was performed at 1065 °C for 1 h 30 min, followed by furnace cooling.

In contrast, the LTSR condition was designed based on differential scanning calorimetry (DSC) analysis. The DSC measurements were performed using a high-temperature DSC instrument (DSC 404 F1, NETZSCH, Germany) over the temperature range from room temperature to 1100 °C at a heating rate of 10 °C/min under Air and Ar atmospheres. Based on the DSC analysis, the specimens were held at 550 °C for 1 h 30 min, followed by furnace cooling.

After the stress-relief treatment, all specimens were subjected to

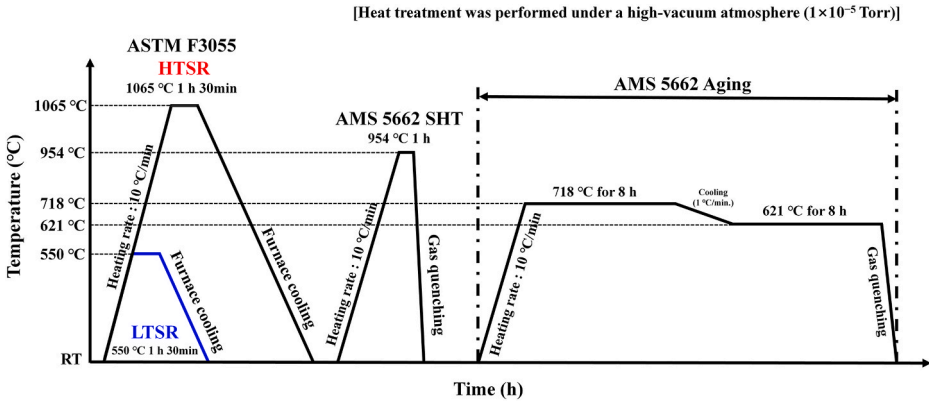


Fig. 2. Schematic illustration of the heat-treatment strategies applied to LPBF-fabricated IN718 specimens, including conventional high-temperature stress relief (HTSR), proposed low-temperature stress relief (LTSR), solution heat treatment (SHT), and aging treatment routes.

Table 2

Summary of the post-processing conditions investigated in the present study, including the stress-relief, solution treatment, aging treatment, and corresponding descriptions for the As-built, HTSR, LTSR, HTST, and LTST conditions.

Condition	Stress-relief treatment	Solution treatment	Aging treatment	Description
As-built	-	-	-	LPBF-fabricated condition
HTSR	1065 °C × 1.5 h + Furnace cooling	-	-	High-temperature stress relief
LTSR	550 °C × 1.5 h + Furnace cooling	-	-	Low-temperature stress relief
HTST	1065 °C × 1.5 h + Furnace cooling	954 °C × 1 h + Gas quenching	718 °C × 8 h + Furnace cooling to 621 °C + 8 h + Furnace cooling	HTSR followed by STA
LTST	550 °C × 1.5 h + Furnace cooling	954 °C × 1 h + Gas quenching	718 °C × 8 h + Furnace cooling to 621 °C + 8 h + Furnace cooling	LTSR followed by STA

identical solution heat treatment (SHT) and aging treatment conditions. The solution heat treatment was conducted at 954 °C for 1 h based on the AMS 5662 specification, followed by gas quenching. Subsequently, the aging treatment was performed at 718 °C for 8 h, followed by cooling to 621 °C at a rate of 1 °C/min. The specimens were then held at 621 °C for 8 h and finally gas quenched. All heat-treatment processes were carried out under a high-vacuum atmosphere of approximately 1×10^{-5} Torr.

2.3. Microstructural characterization and phase analysis

To investigate the microstructural evolution of the LPBF-fabricated As-built specimens and heat-treated specimens (HTSR, LTSR, HTST, and LTST), microstructural characterization was performed after mechanical polishing of the specimen surfaces. Unless otherwise specified, all specimens for OM, SEM, EBSD, XRD, and TEM characterization were sectioned parallel to the build direction (BD) (XZ plane) to ensure consistent comparison among the different heat-treatment conditions. The specimens were sequentially ground using #400–#2400 SiC abrasive papers, followed by additional polishing using 3 µm and 1 µm diamond suspensions. Final polishing was conducted using OP-S colloidal silica to minimize the surface deformation layer.

Electrolytic etching for microstructural observation was carried out using a custom electrolyte composed of 50 mL perchloric acid and 950 mL acetic acid. The etching process was performed at 30 V and 12 °C for 20 s, followed by optical microscopy (OM) analysis. OM observations were conducted using a VHX-5000 microscope (Keyence, Osaka, Japan) to examine the melt-pool morphology formed during the LPBF process and the microstructural evolution after heat treatment.

For more detailed investigation of the microstructural evolution and residual Laves networks, field-emission scanning electron microscopy (FE-SEM; SU8600, Hitachi, Japan) analysis was performed. The SEM observations were conducted on sectioned surfaces parallel to the build direction (BD) to maintain consistency with the LPBF build orientation throughout the microstructural characterization. Particular attention was paid to the evolution of residual Laves networks in interdendritic Nb-rich regions and the subsequent δ-phase precipitation behavior.

Phase evolution and precipitation behavior according to different heat-treatment conditions were analyzed using an X-ray diffractometer (XRD; Empyrean, PANalytical). XRD measurements were performed on the sectioned surface parallel to the build direction (BD) to maintain

consistency with the microstructural characterization. XRD measurements were conducted using Cu Kα radiation over a scanning range of 30°–90° (2θ), with an operating voltage and current of 45 kV and 40 mA, respectively. Variations in diffraction peaks associated with the γ matrix, carbides, and δ phases were comparatively analyzed. The average γ lattice parameters were estimated by whole-pattern Rietveld refinement using X'Pert HighScore Plus (PANalytical). The refinement was performed over an angular range of 30.013–89.839° (2θ) in manual refinement mode with 10 refined parameters. The refinement quality was evaluated using the profile residual ($R_p = 0.22994$), weighted profile residual ($R_{wp} = 0.29442$), expected residual ($R_{exp} = 0.06773$), and goodness-of-fit ($\chi^2 = 4.34695$). The refined lattice parameters were used only for comparative interpretation among the different heat-treatment conditions and were not considered as direct quantitative evidence of Nb redistribution.

Electron backscatter diffraction (EBSD) analysis was conducted to evaluate grain characteristics. EBSD measurements were performed on the final-polished specimens, and inverse pole figure (IPF) maps, image quality (IQ) maps, and kernel average misorientation (KAM) maps were obtained. In addition, changes in grain morphology and grain size distribution according to the heat-treatment conditions were quantitatively compared.

For detailed precipitation analysis and crystallographic characterization, transmission electron microscopy (TEM; JEM-2100F, JEOL, Japan) analysis was performed. TEM lamellae were extracted from the section parallel to the build direction (BD) using a focused ion beam (FIB) technique. The morphology and distribution of precipitates, including residual Laves phases and δ phases, were investigated. Furthermore, selected area diffraction pattern (SADP) and high-resolution TEM (HR-TEM) analyses were conducted to examine the crystallographic orientation relationships between the matrix and precipitates.

2.4. Mechanical properties

Room-temperature and elevated-temperature tensile tests were conducted to evaluate the mechanical properties under different post-processing conditions. Tensile specimens were machined along the Z-axis direction considering the build direction of the LPBF process. To ensure reliable comparison of mechanical properties according to heat-treatment conditions, identical specimen geometry and testing conditions were applied to all specimens.

The tensile specimens were fabricated with dimensions of $10 \times 30 \times 102 \text{ mm}^3$ and machined according to the ASTM E8M standard. Room-temperature tensile tests were conducted at 25 °C, while elevated-temperature tensile tests were performed at 649 °C (1200 °F) based on the high-temperature mechanical property evaluation condition specified for Inconel 718 in the AMS 5662 standard. The test temperature of 649 °C was selected instead of 650 °C because it corresponds to the standard evaluation temperature of 1200 °F widely adopted for aerospace-grade Inconel 718, thereby maintaining consistency with industrial specifications and previously reported high-temperature tensile-property data.

Tensile tests were carried out using a universal testing machine (INSTRON 5589). The testing speed and gauge length were set to 3 mm/min and 25 mm, respectively. Each condition was tested five times, and the average values together with standard deviations of yield strength (YS), ultimate tensile strength (UTS), and elongation (EL) were calculated.

Mechanical property evaluations were performed for the As-built, HTSR, LTSR, HTST, and LTST conditions with five repeated measurements for each condition. Identical specimen geometry and testing conditions were maintained throughout all experiments to comparatively analyze the influence of stress-relief strategy and subsequent heat treatment on the resulting mechanical properties.

3. Results and discussion

3.1. DSC analysis and heat-treatment design

Fig. 3 presents the thermal response behavior of LPBF-fabricated Inconel 718 together with the rationale for designing the stress-relief conditions employed in this study. Due to the rapid solidification characteristics of the LPBF process, LPBF-fabricated Inconel 718 contains non-equilibrium microstructures and residual segregation, resulting in various precipitation and phase-transformation reactions during subsequent heat treatment. Accordingly, differential scanning calorimetry (DSC) analysis was performed to identify the characteristic temperatures associated with major precipitation and dissolution reactions, and the stress-relief conditions were designed based on these thermal responses.

The DSC results revealed a thermal response associated with γ' precipitation at approximately 460 °C. Subsequently, an additional exothermic thermal response associated with γ'' precipitation was initiated near 708 °C, which is similar to the temperature range generally employed for aging treatment. Furthermore, thermal response regions associated with γ'/γ'' dissolution and Laves phase destabilization/dissolution were initiated near 780 °C and 831 °C, respectively.

Meanwhile, the onset of a thermal response associated with δ -phase precipitation was identified near 868 °C, followed by a thermal response associated with δ -phase dissolution initiated near 941 °C. In addition, a carbide dissolution-related thermal response was detected near 1038 °C. These results indicate that different precipitation-initiation behaviors and phase-evolution pathways may be activated depending on the stress-relief temperature during post-heat-treatment processes in LPBF-fabricated Inconel 718.

The conventional HTSR condition was established based on the stress-relief condition specified in ASTM F3055 for LPBF-fabricated Inconel 718. According to the DSC analysis, the HTSR temperature is located near the high-temperature region associated with Laves dissolution and carbide dissolution. This condition is considered a conventional stress-relief strategy that promotes dissolution of residual Laves phases and partial homogenization through enhanced diffusion kinetics at elevated temperatures. In contrast, the proposed LTSR condition is selected within a relatively low-temperature region near the γ' precipitation range. This condition was designed to minimize abrupt microstructural destabilization caused by excessive thermal exposure while

retaining the interdendritic Laves network as stably as possible.

As shown in Fig. 3, the HTSR condition is located adjacent to the Laves dissolution and carbide dissolution regions, whereas the LTSR condition is positioned in the lower-temperature region prior to the major dissolution reactions. Such differences in thermal exposure conditions are expected to result in distinct precipitation behaviors and phase evolution pathways during subsequent aging treatment. Specifically, the HTSR condition is likely to promote rapid collapse of residual Laves networks together with enhanced Nb redistribution, whereas the LTSR condition may allow partial retention of the interdendritic Laves network.

3.2. Microstructural evolution of residual laves networks

Fig. 4 shows the optical microstructural evolution of LPBF-fabricated Inconel 718 subjected to stress-relief and subsequent heat-treatment conditions. In the As-built specimen (Fig. 4(a)), the characteristic semicircular melt-pool morphology typically observed in LPBF-fabricated alloys was clearly identified, together with relatively distinct build-track boundaries formed by rapid solidification behavior. This melt-pool morphology is considered to originate from localized melting/solidification behavior and repeated thermal cycling during the LPBF process. Notably, the optical contrast became relatively pronounced due to non-equilibrium microstructural heterogeneity associated with interdendritic segregation and Nb-rich Laves networks.

Under the HTSR condition (Fig. 4(b)), the melt-pool boundaries became relatively blurred compared with the As-built condition. This behavior is attributed to the activation of diffusion kinetics during the high-temperature stress-relief process, which partially relaxed the segregation structure and interdendritic network morphology formed during LPBF fabrication, including the remaining interdendritic Laves morphology. By comparison, under the LTSR condition (Fig. 4(c)), the melt-pool morphology formed in the As-built condition remained relatively well preserved, and the build-track boundaries were still clearly distinguishable. These results indicate that abrupt microstructural destabilization was relatively suppressed under the low-temperature stress-relief condition.

After subsequent standard heat treatment, the HTST condition (Fig. 4(d)) exhibited a relatively homogenized microstructure in which most of the original melt-pool morphology disappeared. This behavior is attributed to the combined effects of the prior high-temperature stress-relief treatment and the subsequent solution heat treatment, which promoted elemental homogenization and recovery of the build-induced microstructure. Consequently, the chemical segregation responsible for the etching contrast at the melt-pool boundaries was substantially reduced, making the original melt-pool morphology indistinguishable in the OM images. In addition, localized precipitation traces were observed along several grain-boundary regions. Conversely, the LTST condition (Fig. 4(e)) partially retained traces of the build-induced morphology compared with the HTST condition, while fine precipitation traces were distributed more uniformly throughout the microstructure. The remaining melt-pool traces observed in the revised Fig. 4 indicate that the lower stress-relief temperature suppressed excessive homogenization during the initial stress-relief stage, thereby preserving portions of the build-induced microstructural features. These results suggest that thermal exposure during the stress-relief stage can significantly influence microstructural stability and subsequent precipitation behavior during post-heat-treatment processes.

Fig. 5 presents SEM observations showing the evolution of residual Laves morphology and precipitation behavior under different stress-relief and subsequent heat-treatment conditions. In the As-built specimen (Fig. 5(a)), a continuously interconnected fine cellular/Laves network structure was clearly observed along the interdendritic regions. ImageJ-based binary image analysis (Fig. 5 and Table 3) revealed that the retained Laves-network area fraction was approximately 28.2%, quantitatively confirming the well-developed interconnected network

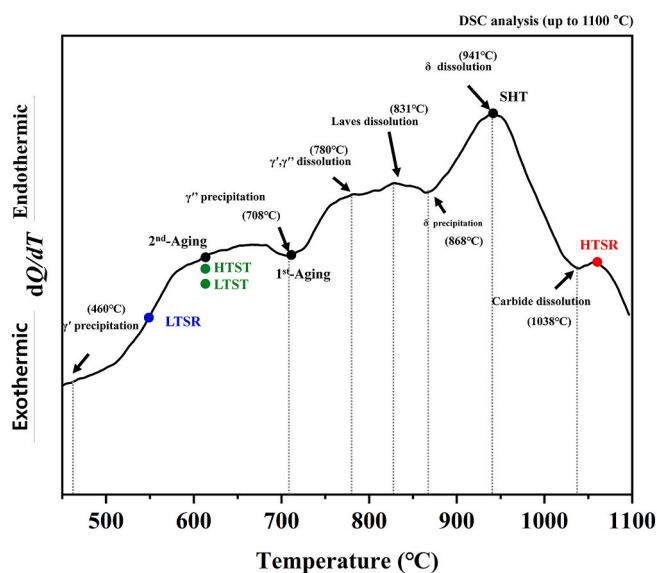


Fig. 3. DSC thermogram of LPBF-fabricated Inconel 718 showing the characteristic thermal responses associated with γ'/γ'' phases, Laves phase, δ phase, and carbides, together with the selected HTSR, LTSR, and SHT temperature regions.

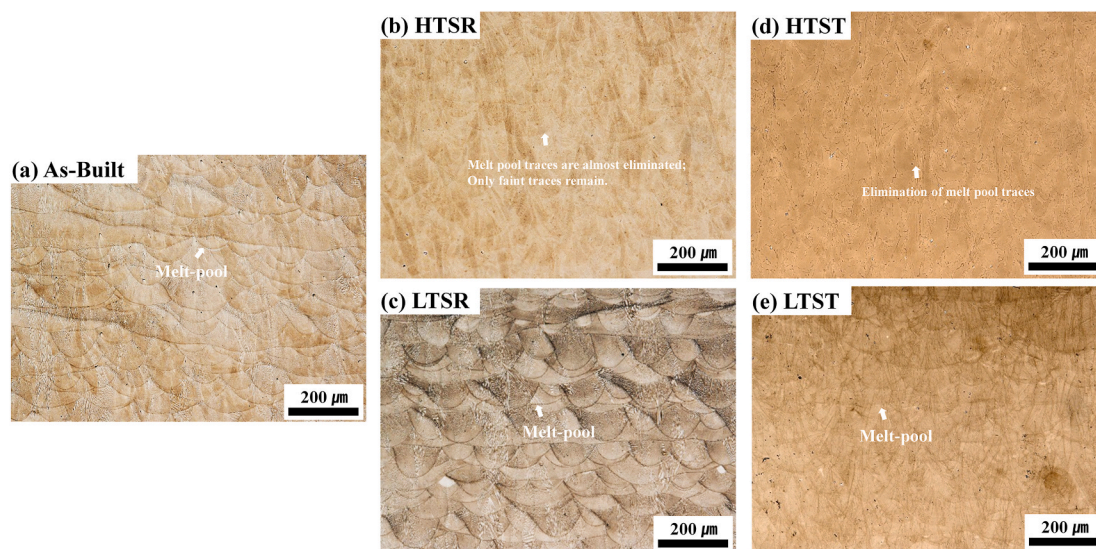


Fig. 4. Optical microstructures of LPBF-fabricated Inconel 718 under different post-processing conditions: (a) As-built, (b) HTSR, (c) LTSR, (d) HTST, and (e) LTST.

morphology. This network morphology is considered a representative non-equilibrium microstructure formed by rapid solidification during the LPBF process, exhibiting localized Nb-rich segregation along the interdendritic regions.

Under the HTSR condition (Fig. 5(b)), the initially fine network morphology observed in the As-built condition was substantially disrupted, and only partially discontinuous residual phases remained. Consistent with the ImageJ-based quantitative analysis (Fig. 5 and Table 3), the segmented white-area fraction decreased to approximately 10.7%, indicating a significant reduction of the retained Laves-network morphology after high-temperature stress relief. In addition, fine γ'' -like precipitates are observed within the matrix [32]. This behavior is attributed to partial homogenization of the residual Laves network during the high-temperature stress-relief process above 1000 °C. Subsequently, γ'' precipitates reprecipitate within the matrix during furnace cooling, resulting in a precipitation morphology distinct from that of the As-built condition.

By comparison, the LTSR condition (Fig. 5(c)) exhibited relatively continuous retention of the fine network morphology formed in the As-built condition. ImageJ analysis (Fig. 5 and Table 3) showed a retained Laves-network area fraction of approximately 31.1%, which is comparable to that of the As-built condition and quantitatively supports preservation of the interdendritic Laves network during low-temperature stress relief. In particular, the interdendritic network structure remained comparatively stable relative to the HTSR condition, and the abrupt morphology collapse observed under HTSR was not detected. These results indicate that rapid destabilization of the interdendritic Laves network was effectively suppressed under the low-temperature stress-relief condition.

Following subsequent standard heat treatment, the HTST condition (Fig. 5(d)) exhibited the formation of fine γ'' precipitates within the matrix together with concentrated precipitation of coarse needle-like δ precipitates along grain boundaries and interdendritic regions. The ImageJ-based binary analysis (Fig. 5 and Table 3) yielded a segmented white-area fraction of approximately 4.7%, corresponding to a limited amount of coarse precipitates remaining after dissolution of the original Laves network. In several regions, coarse plate-like morphologies were also observed, which are considered to originate from rapid Laves-network collapse during the prior HTSR process combined with precipitation coarsening during the subsequent aging treatment [33]. Notably, the coarse δ phases formed along grain boundaries exhibited a pronounced localized precipitation tendency.

By contrast, the LTST condition (Fig. 5(e)) exhibited a relatively finer

and more dispersed precipitation morphology compared with the HTST condition. The ImageJ-based binary analysis (Fig. 5 and Table 3) measured a segmented white-area fraction of approximately 7.8%, indicating a larger fraction of finely dispersed precipitates than in the HTST condition. High-magnification FE-SEM images revealed that fine needle-like δ precipitates were more uniformly distributed throughout the matrix, whereas the coarse grain-boundary δ precipitation observed in the HTST condition was significantly reduced. In addition, partial retention of residual network-like morphology was observed in several regions. These observations indicate that partial retention of the interdendritic Laves network under the LTSR condition promoted a finer and more dispersed precipitation pathway during the subsequent aging process.

Therefore, thermal exposure during the stress-relief stage is considered to directly influence residual Laves stability and subsequent precipitation behavior. The qualitative SEM observations are further supported by the ImageJ-based binary image analysis (Fig. 5) and the quantitative white-area fractions summarized in Table 3, providing objective evidence for the evolution of the retained Laves network and subsequent precipitation behavior under different post-processing conditions. Under the HTSR condition, the original build-induced network morphology rapidly collapsed owing to rapid homogenization and dissolution-assisted Laves-network breakdown, which subsequently led to localized formation of coarse δ precipitates along grain boundaries and interdendritic regions in the HTST condition. In contrast, under the LTSR condition, the build-induced microstructure was partially retained, resulting in relative preservation of residual Nb segregation tendencies and the formation of finer and more uniformly dispersed precipitation morphology in the LTST condition. These results suggest that residual microstructure evolution during the stress-relief stage can directly affect subsequent precipitation pathways and final microstructural development following standard heat treatment. These results, together with the quantitative ImageJ analysis presented in Table 3, demonstrate that the evolution of the retained Laves network is governed by the stress-relief strategy and subsequently influences the precipitation pathway during the standard heat-treatment process. The identification of the observed secondary phases and precipitates was based on the combined evidence obtained from the XRD, TEM, SADP, and HRTEM/FFT analyses presented in this study, rather than solely on the SEM morphologies.

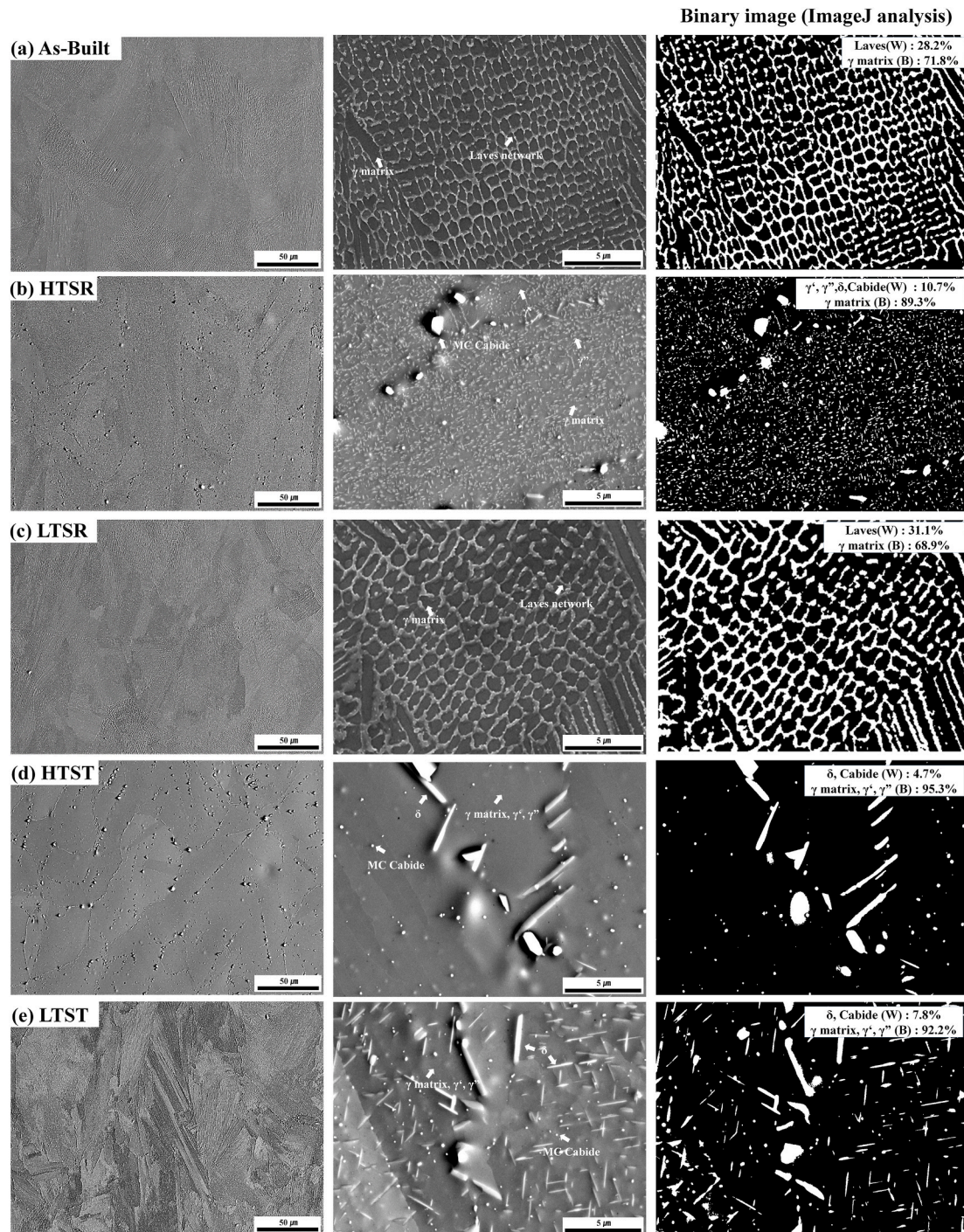


Fig. 5. SEM microstructures showing the evolution of residual Laves morphology and precipitation behavior under different post-processing conditions: (a) As-built, (b) HTSR, (c) LTSR, (d) HTST, and (e) LTST. Low- and high-magnification images are presented for each condition.

3.3. Grain evolution behavior

Fig. 6 presents the EBSD analysis results showing the evolution of grain characteristics in LPBF-fabricated Inconel 718 under different heat-treatment conditions. Inverse pole figure (IPF) maps, grain boundary maps, kernel average misorientation (KAM, °) maps, and grain size distributions were comparatively analyzed for each condition.

In the As-built specimen (Fig. 6(a)), elongated grain morphology characteristic of the LPBF process was observed along the build direction (BD). The grain boundary map revealed that the microstructure was predominantly composed of high-angle grain boundaries (HAGBs), with

a smaller fraction of low-angle grain boundaries (LAGBs), while the average grain size remained approximately $48.7 \pm 12.9 \mu\text{m}$. In addition, relatively high local strain distribution was identified in the KAM map owing to the cellular substructure formed during rapid solidification. The average KAM value were measured to be approximately 0.75°, respectively.

Under the HTSR condition (Fig. 6(b)), partial grain coarsening was observed compared with the As-built condition, and the average grain size increases to approximately $53.6 \pm 14.9 \mu\text{m}$. The grain boundary characteristics remained generally similar to those of the As-built condition, although a slight increase in the HAGB fraction was observed. A

Table 3

Quantitative ImageJ-based binary image analysis showing the segmented phases (white area), measured white area fractions, and corresponding microstructural characteristics of LPBF-fabricated Inconel 718 under different post-processing conditions.

Condition	Segmented phase (white area)	White area fraction (%)	Remarks
As-built	Retained Laves-network	28.2	Laves-network Clearly observed
HTSR	δ phase + MC carbides (+ γ' , γ'')	10.7	Discontinuous Precipitates
LTSR	Retained Laves-network	31.1	Laves-network Well preserved
HTST	δ phase + MC carbides	4.7	Few coarse Precipitates
LTST	δ phase + MC carbides	7.8	Fine precipitates distributed

locally reduced KAM region was also observed in the upper-right portion of the analyzed area. However, this localized feature should not be interpreted as direct evidence of recrystallization or substantial recovery because additional EBSD analyses, such as grain orientation spread (GOS), grain reference orientation deviation (GROD), or recrystallization classification, were not performed in the present study. Instead, this region is interpreted as a locally reduced orientation-gradient region that may be associated with partial microstructural evolution during the HTSR treatment.

In addition, the average KAM value slightly decreased to approximately 0.73° , together with a partial reduction in localized strain concentration regions. Considering the relatively small difference in the average KAM values, this observation alone should not be regarded as definitive evidence of recovery. Instead, the KAM results are interpreted as supporting evidence of local crystallographic orientation gradients, while the primary microstructural evolution is evidenced by the retained Laves network, precipitation evolution, and grain boundary characteristics discussed in Sections 3.2–3.4. Meanwhile, the LTSR condition (Fig. 6(c)) retained elongated grain morphology similar to that of the As-built condition. The average grain size is approximately $48.8 \pm 12.3 \mu\text{m}$, indicating that grain growth was relatively limited compared with the HTSR condition. The grain boundary map also confirmed that the build-induced grain boundary characteristics were largely preserved after low-temperature stress relief. Furthermore, the average KAM value increased slightly to approximately 0.80° . This increase should not be interpreted as an increase in the macroscopic residual stress. Instead, the KAM map reflects local crystallographic orientation gradients, which may arise from retained dislocation structures, local lattice distortion associated with the build-induced microstructure, and microstructural heterogeneity. Because the LTSR treatment was intentionally designed to preserve the residual Laves network while suppressing extensive recovery, the retained local orientation gradients are considered consistent with preservation of the build-induced microstructure rather than with an increase in residual stress. These results indicate that extensive recovery and recrystallization were relatively suppressed under the low-temperature stress-relief condition.

After subsequent standard heat treatment, the HTST condition (Fig. 6(d)) exhibited an increase in average grain size to approximately $55.1 \pm 14.4 \mu\text{m}$ together with partial grain coarsening tendencies in several regions. The grain boundary map indicated a slight increase in HAGBs associated with limited grain growth during the subsequent heat treatment. The average KAM value is approximately 0.77° .

In contrast, the LTST condition (Fig. 6(e)) showed a relatively smaller average grain size of approximately $50.3 \pm 14.3 \mu\text{m}$ together with the lowest average KAM value ($\sim 0.63^\circ$) among all conditions, indicating more restricted grain growth and relatively uniform residual strain distribution compared with the HTST condition. Despite the subsequent aging treatment, the grain boundary characteristics remained comparable to those of the As-built and LTSR conditions, indicating that

extensive recrystallization did not occur. In general, a reduction in KAM distribution indicates alleviation of local strain and residual stress. In the present study, this behavior is considered closely related to the fine and uniformly distributed δ precipitation morphology formed under the LTST condition, which contributed to more homogeneous relaxation of local stress distribution within the matrix.

Under the HTST condition, coarse δ precipitates were preferentially concentrated along grain boundaries, whereas the LTST condition exhibited relatively uniform dispersion of fine needle-like δ precipitates throughout the matrix. In general, coarse grain-boundary δ precipitation may induce localized stress concentration and non-uniform strain accumulation. In contrast, the fine and dispersed δ precipitation morphology formed under the LTST condition is considered to contribute to stabilization of strain distribution within the matrix. These observations are consistent with the relatively low KAM tendency observed in the LTST condition.

Notably, although grain growth in the LTST condition was relatively limited compared with the HTST condition, more uniform precipitation behavior was achieved. This behavior is interpreted to result not simply from suppression of grain coarsening, but rather from the retained interdendritic Laves network during the stress-relief stage together with the subsequently formed fine dispersed δ precipitation morphology, both of which contributed more effectively to residual strain relaxation during aging treatment.

Nevertheless, all conditions generally retained elongated grain morphology and build-induced grain structures to a considerable extent, while differences in average grain size remained relatively limited. These observations suggest that the microstructural evolution and mechanical property changes observed in the present study are more strongly associated with precipitation morphology and residual microstructure evolution than with grain growth behavior alone.

In particular, the HTST condition exhibited relatively coarse δ precipitation together with localized precipitation concentration tendencies, whereas the LTST condition showed finer and more uniformly distributed precipitation behavior. However, EBSD analysis did not reveal any extreme differences in grain structure between the two conditions. Therefore, the mechanical property variations observed in this study are considered to be governed more predominantly by changes in precipitation pathways induced by different stress-relief strategies rather than by a simple grain-size effect.

3.4. Phase evolution and precipitation behavior

Fig. 7 presents the XRD analysis results showing phase evolution and precipitation behavior in LPBF-fabricated Inconel 718 under different heat-treatment conditions. Major diffraction peaks corresponding to the γ matrix were observed under all conditions, while variations in the peak intensities associated with δ phases and carbides were identified depending on the stress-relief and subsequent heat-treatment conditions. In addition, the average γ lattice parameter was estimated from Rietveld refinement of the XRD patterns and is presented primarily for comparative purposes among the different heat-treatment conditions. The corresponding results are summarized in Table 4.

In the As-built and stress-relief conditions, diffraction peaks corresponding primarily to the γ matrix were observed, while no significant peak-position differences were detected between the HTSR and LTSR conditions. These results indicate that, during the stress-relief stage, interdendritic Laves network evolution and localized segregation redistribution behavior were more dominant than bulk phase transformation. As summarized in Table 4, the HTSR condition exhibited a decrease in the average γ lattice parameter compared with the As-built condition. However, the refined lattice parameter should not be interpreted as a unique indicator of Nb redistribution because it may also be influenced by residual stress, coherent lattice strains associated with γ/γ'' precipitates, alloying-element partitioning, and experimental uncertainty. Therefore, the observed variation is interpreted only as a

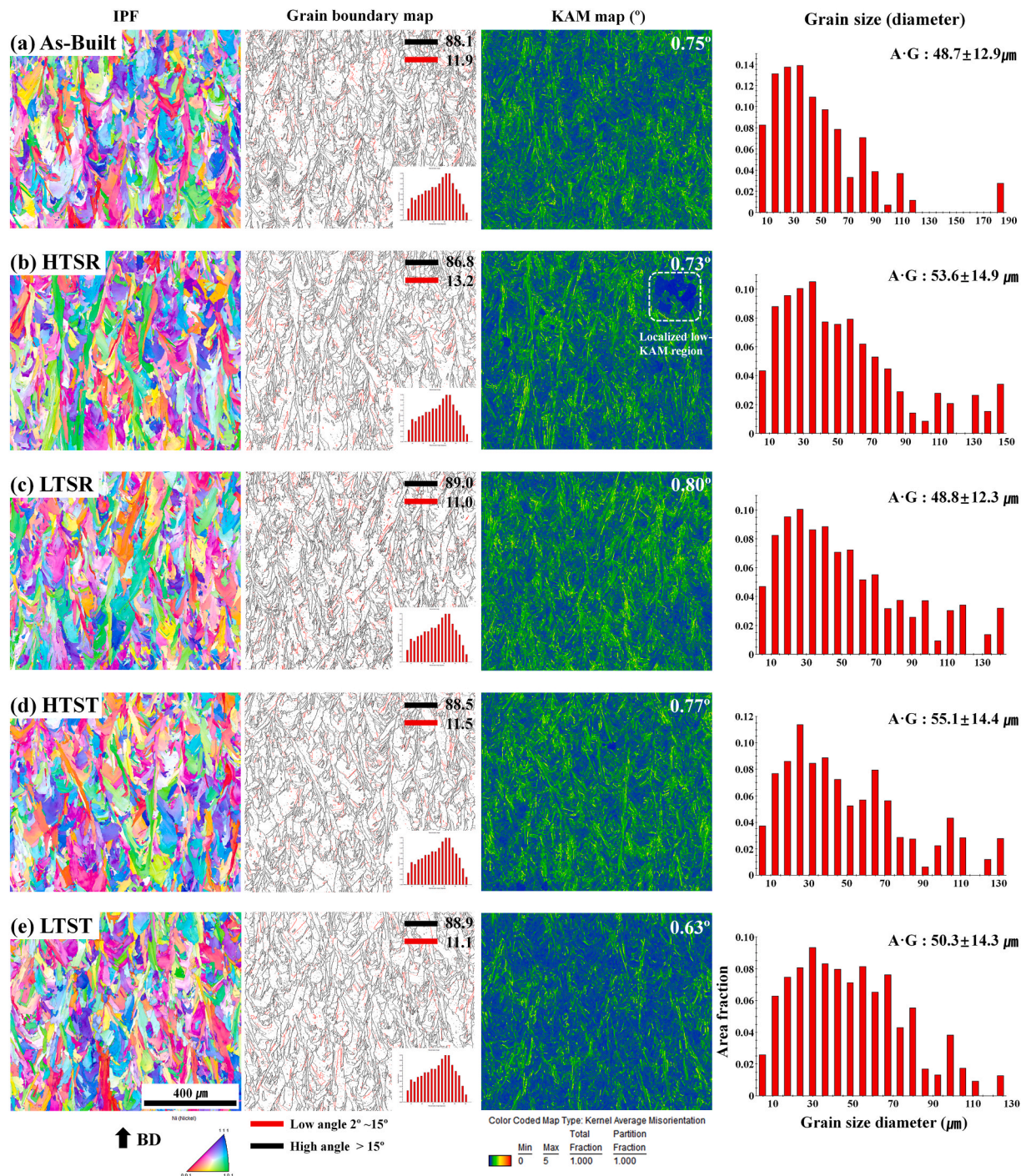


Fig. 6. EBSD characterization of LPBF-fabricated Inconel 718 subjected to different post-processing routes: inverse pole figure (IPF) maps, grain boundary maps, kernel average misorientation (KAM, °) maps, and grain size distributions for (a) As-built, (b) HTSR, (c) LTSR, (d) HTST, and (e) LTST specimens. The average KAM values are expressed in degrees (°) and rounded to two decimal places in accordance with the measurement accuracy of EBSD.

comparative trend that is consistent with the combined microstructural observations obtained from XRD, SEM, and precipitation analyses. By comparison, the LTSR condition maintained a relatively higher average γ lattice parameter, which is likewise interpreted as a comparative trend consistent with partial retention of the original segregation structure and interdendritic Laves morphology, rather than as direct evidence of Nb redistribution. In contrast, the LTST condition maintained a relatively higher average γ lattice parameter, which is likewise interpreted only in conjunction with the XRD peak characteristics, SEM observations, retained Laves network, and precipitation morphology. Therefore,

the refined lattice parameter is used as a complementary indicator of the overall microstructural evolution rather than as an independent measure of Nb redistribution. After subsequent standard heat treatment, however, differences in the peak intensities associated with δ phases and carbides became more pronounced in the HTST and LTST conditions.

In particular, the HTST condition exhibited a relatively increased δ (211) peak intensity, which is consistent with the coarse grain-boundary δ precipitation observed in the SEM analysis. In addition, carbide-related peaks became relatively more distinguishable, which is considered to result from localized precipitation concentration tendencies

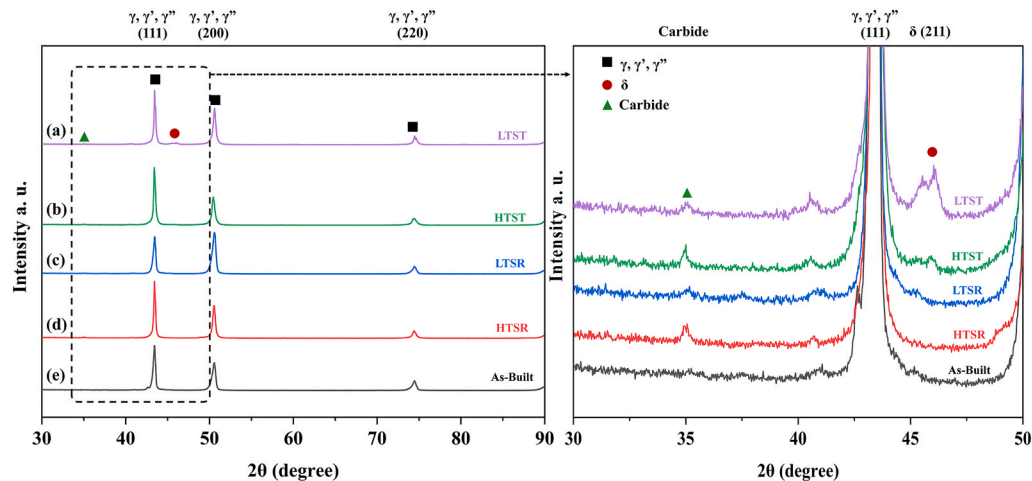


Fig. 7. XRD patterns of LPBF-fabricated Inconel 718 under different post-processing conditions: (a) As-built, (b) HTSR, (c) LTSR, (d) HTST, and (e) LTST, showing the evolution of γ matrix, δ phase, and carbide-related diffraction peaks.

Table 4
Average γ lattice parameters and characteristic precipitation behavior of LPBF-fabricated Inconel 718 under different post-processing conditions.

Condition	Average γ lattice parameter (Å) (111),(200),(220)	FWHM (111) (°2 θ)	FWHM (200) (°2 θ)	FWHM (220) (°2 θ)	Relative peak shift tendency	Estimated Nb redistribution tendency	Characteristic precipitation behavior
As-built	3.612	0.333	0.371	0.568	Reference	Moderate	Fine interdendritic Laves network
HTSR	3.607	0.263	0.319	0.534	Slight right shift	Increased homogenization and Nb redistribution	Partial dissolution of the Laves network
LTSR	3.611	0.368	0.368	0.368	Minor shift	Partial retention of Nb segregation	Evidence-based
HTST	3.601	0.335	0.405	0.675	Pronounced right shift	Reduced Nb concentration in γ matrix due to localized precipitation	Localized coarse δ precipitation
LTST	3.601	0.283	0.341	0.564	Broadening with minor shift	Partial Nb retention and incomplete lattice relaxation	Fine and dispersed δ precipitation

※ The lattice parameters were obtained by whole-pattern Rietveld refinement using X'Pert HighScore Plus (manual refinement; $R_p = 0.22994$, $R_{wp} = 0.29442$, $\chi^2 = 4.34695$) and are presented for comparative purposes. Small differences should not be interpreted as direct quantitative evidence of Nb redistribution.

formed after rapid homogenization during the prior HTSR process. Furthermore, slight peak broadening of several γ matrix peaks was observed, which may be associated with changes in precipitation behavior together with Nb redistribution and localized lattice distortion within the γ matrix during heat treatment. Notably, the HTST condition exhibited the lowest average γ lattice parameter among all conditions. Considering the practical uncertainty associated with the XRD measurements and Rietveld refinement, these lattice parameter values are intended for comparative interpretation rather than direct quantitative evaluation of Nb redistribution. This behavior is interpreted to result from the relative reduction of Nb solubility in the γ matrix caused by localized coarse δ precipitation during subsequent aging following the HTSR process.

Compared with the HTST condition, the LTST condition exhibited relatively broadened δ -related peaks compared with the HTST condition. The FWHM values of the representative γ peaks, including the (111), (200), and (220) reflections, were therefore summarized in Table 4 to provide a comparative peak-shape analysis. However, peak broadening should not be regarded as direct evidence of finer precipitates because it can also arise from microstrain, retained dislocation structures, overlapping phase peaks, and instrumental broadening. Accordingly, the broadened peak tendency observed in the LTST condition is interpreted only as a comparative feature associated with combined microstructural changes and is considered together with the SEM-observed precipitation morphology and retained Laves network. In addition, the carbide peak intensity tended to decrease relative to the HTST condition, suggesting a more homogeneous precipitation behavior rather than localized carbide formation. Moreover, broadened γ -matrix

peak characteristics were maintained relative to the HTST condition, indicating that localized lattice distortion and microstructural heterogeneity were not completely relaxed during the low-temperature stress-relief route.

Indeed, the average γ lattice parameter of the LTST condition remained relatively higher than that of the HTST condition. However, considering the practical uncertainty associated with the XRD measurements and Rietveld refinement, this small difference alone cannot be regarded as definitive evidence of greater Nb retention in the γ matrix under the LTST condition. Instead, the refined lattice parameters are interpreted together with the XRD peak characteristics, SEM observations, retained Laves network, and precipitation morphology, all of which consistently suggest delayed Nb redistribution and a finer precipitation pathway in the LTST condition. These observations should be interpreted as comparative trends rather than direct quantitative evidence of Nb redistribution. These results suggest that differences in interdendritic Laves network evolution during the stress-relief stage can subsequently influence phase evolution and precipitation pathways during post-heat-treatment processes.

Fig. 8 presents the TEM and SADP analysis results of the HTST condition. Under the HTST condition, δ precipitates exhibited relatively coarse growth behavior after the prior HTSR process. Therefore, TEM analysis was primarily conducted in the γ matrix regions rather than in areas dominated by coarse δ precipitation. Bright-field TEM images (Fig. 8(a and b)) revealed relatively uniform distributions of fine precipitates within the γ matrix, although localized differences in precipitation contrast were observed in several regions.

High-magnification TEM and HR-TEM analyses (Fig. 8(d)) confirmed

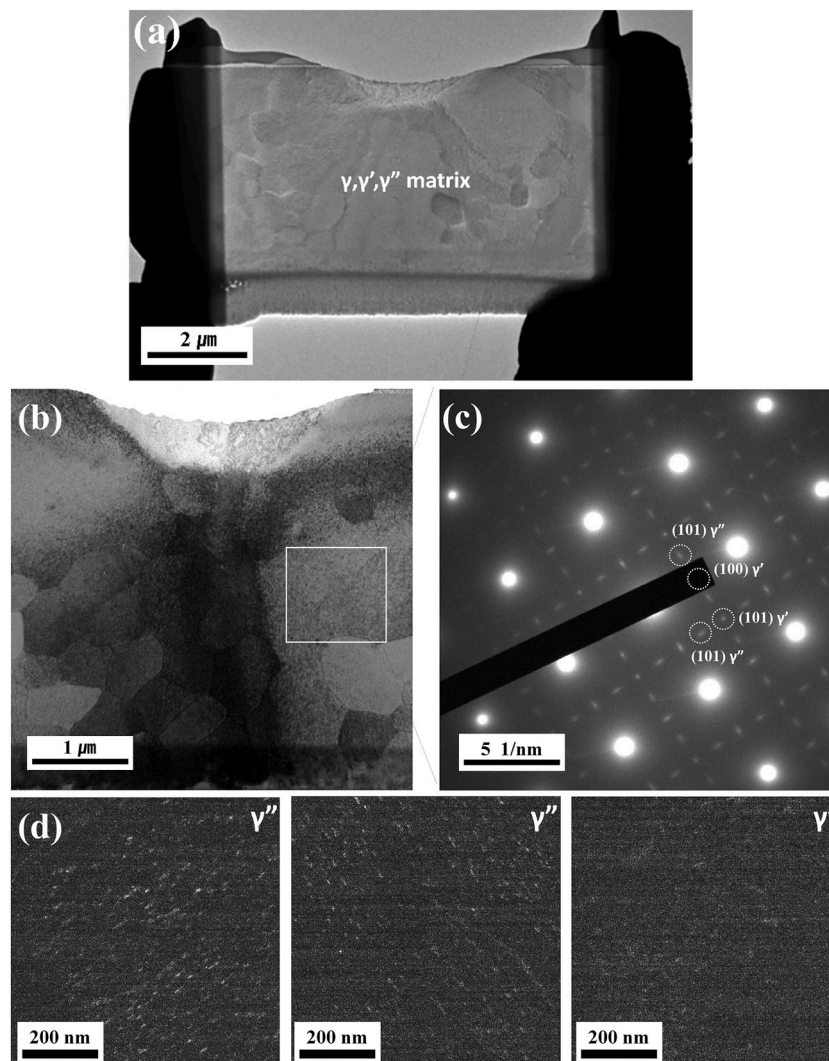


Fig. 8. TEM and diffraction analysis results of the HTST condition: (a,b) TEM images of the γ matrix region, (c) SADP pattern showing γ'/γ'' -related diffraction spots, and (d) HR-TEM images showing fine γ'/γ'' strengthening precipitates formed after HTSR and subsequent standard heat treatment.

the presence of γ' and γ'' strengthening precipitates within the γ matrix under the HTST condition. The HR-TEM observations were primarily employed to identify the crystallographic characteristics of the nano-scale precipitates. Quantitative determination of lattice parameters based on measured interplanar spacings was beyond the scope of the present study. Although no quantitative statistical analysis of precipitate size, number density, or volume fraction was performed in the present study, the TEM observations confirmed the formation of γ' and γ'' strengthening precipitates within the observed γ -matrix regions. For this reason, the TEM analysis was used primarily to identify the precipitation characteristics and crystallographic features rather than to quantitatively evaluate the strengthening contribution of the individual precipitate phases. In addition, several precipitates exhibited alignment along specific crystallographic directions, suggesting that the precipitation behavior was influenced by orientation relationships with the γ matrix.

The SADP analysis results (Fig. 8(c)) showed superlattice diffraction spots associated with γ' and γ'' strengthening phases together with the fundamental diffraction spots of the γ matrix. Notably, the γ'' -related diffraction spots exhibited preferential alignment along specific crystallographic directions of the γ matrix, indicating the formation of partial crystallographic coherence and orientation relationships between the γ matrix and γ'' precipitates. These results demonstrate that γ'/γ'' strengthening precipitates remained stably distributed within the γ

matrix even under the HTST condition.

Meanwhile, as observed in the SEM analysis, the HTST condition exhibited a dominant tendency for coarse δ precipitation along grain boundaries and prior interdendritic regions. This behavior is considered to result from rapid homogenization and dissolution of the interdendritic Laves network during the prior HTSR process, followed by enhanced localized precipitation coarsening during subsequent aging treatment. Therefore, the TEM results presented in Fig. 8 not only reveal the characteristics of the strengthening precipitates formed within the γ matrix under the HTST condition, but also suggest that precipitation evolution under the HTST condition proceeded together with localized coarse precipitation tendencies.

In contrast, Fig. 9 presents the TEM and diffraction analysis results of the LTST condition. Compared with the HTST condition, the LTST condition exhibited a relatively finer and more uniformly dispersed precipitation morphology within the observed TEM regions. Low-magnification TEM images (Fig. 9(a and b)) revealed a relative reduction in coarse grain-boundary precipitation, while fine needle-like precipitates were distributed more uniformly throughout the γ matrix.

TEM and SADP analyses confirmed the formation of relatively stable interfacial structures between the fine needle-like γ'' precipitates and the γ matrix under the LTST condition. Based on the observed TEM images, the precipitates appeared to exhibit relatively smaller sizes and a more dispersed morphology than those observed under the HTST condition.

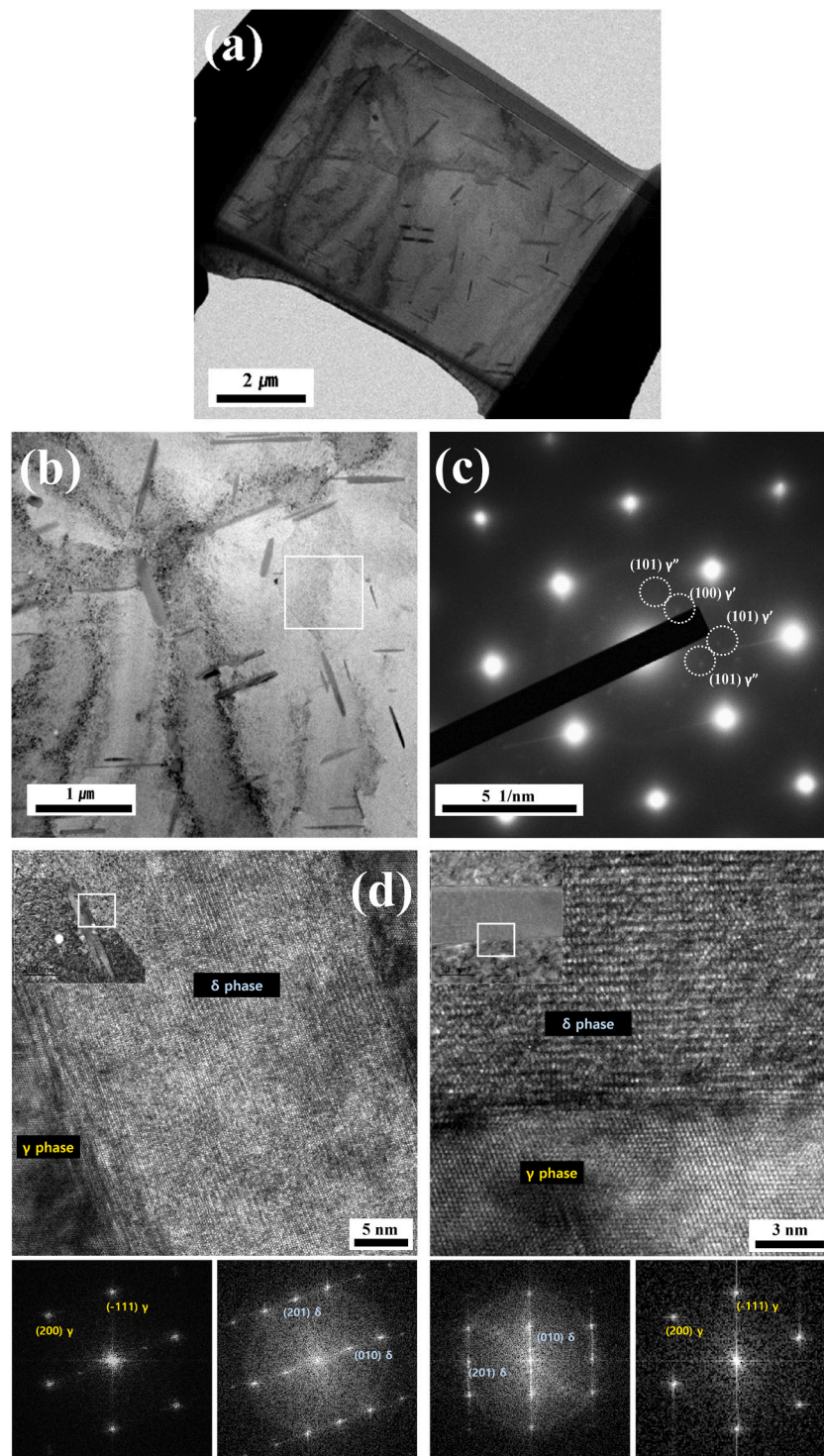


Fig. 9. TEM and diffraction analysis results of the LTST condition showing fine and dispersed precipitation morphology together with crystallographic orientation relationships between the γ matrix and precipitates after low-temperature stress relief and subsequent standard heat treatment.

However, no quantitative measurements of precipitate size, aspect ratio, number density, spacing, or volume fraction were performed in the present study. Therefore, these observations should be regarded as comparative observations within the analyzed TEM regions. Specifically, the SADP pattern (Fig. 9(c)) clearly showed superlattice diffraction spots associated with γ' and γ'' strengthening phases together with the fundamental diffraction spots of the γ matrix. Several γ'' -related diffraction spots exhibited preferential alignment along specific crystallographic directions of the γ matrix, suggesting the formation of

partial crystallographic coherence and orientation relationships between the γ matrix and γ'' precipitates.

Notably, the γ'' -related diffraction spots were qualitatively consistent with orientation relationships close to $[100]\gamma'' // [100]\gamma$ and $\{001\}\gamma'' // \{001\}\gamma$. Because the selected-area diffraction pattern may contain overlapping reflections from the γ matrix and multiple precipitate variants, these diffraction features are interpreted as crystallographic evidence rather than definitive orientation relationships. Such orientation relationships are likely associated with alleviation of lattice misfit and

enhanced interfacial stability between the γ matrix and γ'' precipitates. In addition, γ'' -related diffraction spots aligned along mutually orthogonal directions were observed in the SADP pattern, suggesting the possible formation of different γ'' precipitate variants within the γ matrix. However, these variant morphologies were inferred primarily through crystallographic interpretation of the SADP patterns rather than being directly distinguishable in the TEM bright-field images.

High-resolution TEM and FFT analyses (Fig. 9(d)) further revealed relatively distinct interfacial structures between the γ matrix and δ precipitates, together with diffraction patterns corresponding to the γ and δ phases. These analyses were intended to examine the crystallographic characteristics and interfacial structures of the precipitates rather than to quantitatively determine lattice parameters from interplanar-spacing measurements. Notably, several δ precipitates exhibited specific crystallographic alignment relationships with the γ matrix, indicating partial lattice matching tendencies at the γ/δ interfaces.

The TEM observations indicated that the δ precipitates in the LTST condition exhibited a relatively finer and more dispersed morphology than those observed in the HTST condition within the analyzed regions. However, these observations should be interpreted as comparative observations rather than quantitative evaluations because statistical measurements of precipitate size, aspect ratio, number density, spacing, and volume fraction were beyond the scope of the present study. Rather than attributing the mechanical-property differences to the fine δ precipitates alone, the present results suggest that the preserved interdendritic structure influenced the subsequent precipitation pathway through delayed Nb redistribution, thereby affecting the overall evolution of the γ'/γ'' and δ precipitates during aging. This behavior is attributed to the partial retention of the interdendritic Laves network under the LTST condition, which likely promoted more gradual Nb redistribution and moderated the overall precipitation evolution during subsequent aging treatment. Rather than indicating that the fine δ precipitates alone were responsible for the improved mechanical properties, the present observations suggest that the retained Laves network

influenced the subsequent precipitation pathway, including the evolution of the γ'/γ'' strengthening precipitates and the δ phase. As a result, localized precipitation coarsening tendencies were relatively suppressed under the LTST condition, leading to a more homogeneous precipitation morphology within the observed γ matrix.

Therefore, thermal exposure during the stress-relief stage is considered to directly influence not only interdendritic Laves network evolution but also subsequent precipitation pathways and γ/δ interfacial structure evolution during aging treatment. In particular, the HTSR condition promoted localized coarse δ precipitation following rapid homogenization, whereas the LTST condition allowed partial retention of the residual interdendritic Laves network, resulting in a finer and more uniformly distributed precipitation morphology within the observed regions. This precipitation morphology is interpreted as part of the overall precipitation evolution accompanying the γ'/γ'' strengthening response rather than evidence that the δ precipitates themselves constitute the primary strengthening phase.

3.5. Effect of stress-relief strategy on room-temperature and elevated-temperature tensile behavior

Fig. 10 and Table 5 present the room-temperature and elevated-temperature tensile properties of LPBF-fabricated Inconel 718 under different stress-relief and subsequent heat-treatment conditions. Ultimate tensile strength (UTS), yield strength (YS), elongation (EL), and engineering stress–strain curves were comparatively analyzed at room temperature and 649 °C.

The elevated-temperature tensile tests were performed at 649 °C (1200 °F) because this temperature is widely adopted as the standard evaluation temperature for Inconel 718 in aerospace applications and the AMS 5662 specification, thereby enabling direct comparison with previously reported high-temperature tensile-property data. The As-built specimen exhibited relatively low yield strength and tensile strength while maintaining comparatively high elongation. This behavior is attributed to the limited formation of strengthening

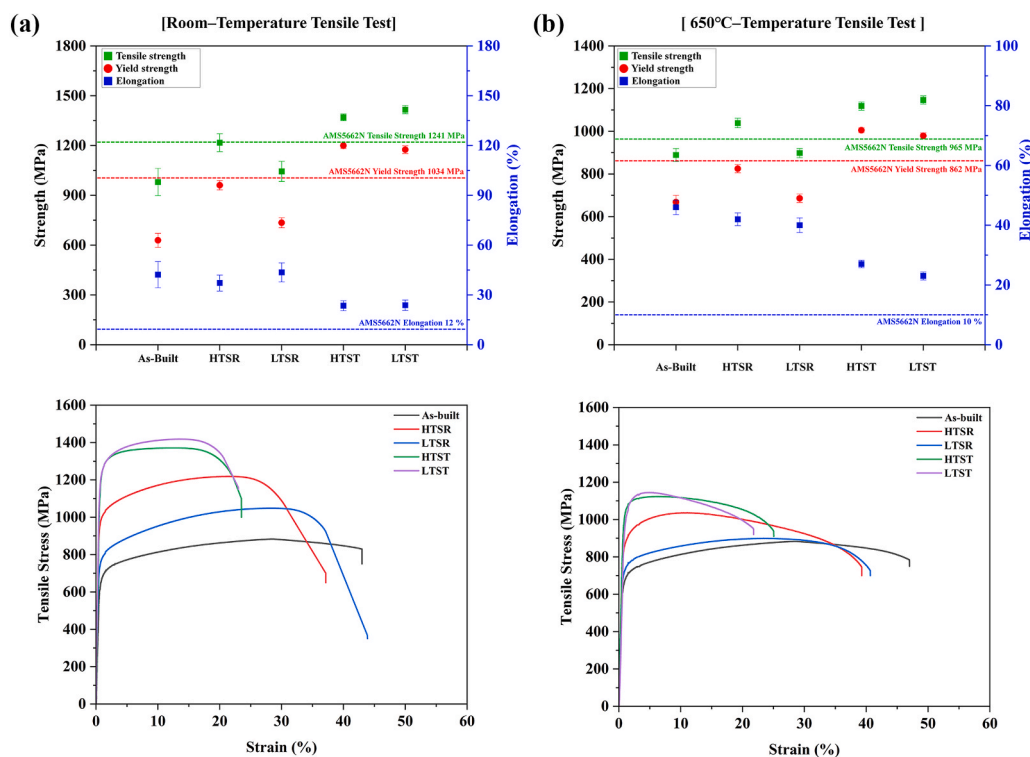


Fig. 10. Room-temperature and elevated-temperature tensile properties of LPBF-fabricated Inconel 718 under different post-processing conditions: (a) room-temperature tensile properties and engineering stress–strain curves, and (b) elevated-temperature tensile properties and engineering stress–strain curves at 649 °C.

Table 5

Average room-temperature and 649 °C tensile properties of LPBF-fabricated Inconel 718 under different post-processing conditions, including tensile strength (TS), yield strength (YS), and elongation (EL.) with corresponding standard deviations.

Room Temp. Tensile Test.	As-built	HTSR	LTSR	HTST	LTST	649°C Tensile Test	As-built	HTSR	LTSR	HTST	LTST
T.S (MPa)	980.2 ±82.2	1217.1±54.1	1044.6±60.8	1370.1±20.7	1416.8±24.5	T.S (MPa)	889.3 ±30.2	1039.7±22.4	898.4 ±21.5	1118.5±19.2	1147.3±18.9
Y.S (MPa)	629.3 ±42.5	961.2 ±28.4	735.7 ±30.5	1199.2±16.7	1175.5±23.4	Y.S (MPa)	668.8 ±31.5	825.9 ±19.5	686.9 ±20.1	1005.1±11.3	979.7 ±13.2
EL. (%)	42.2 ±7.8	37.2 ±4.8	43.6 ±5.7	23.5 ±2.98	23.8 ±3.1	EL. (%)	46.7 ±2.4	42.5 ±2.1	40.2 ±2.4	27.4 ±1.2	23.5 ±1.3

precipitates despite the presence of cellular substructures and residual Laves networks formed during the LPBF process.

Under the HTSR condition, both yield strength and tensile strength increased compared with the As-built condition. This behavior is considered to result from partial homogenization and partial formation of γ'/γ'' strengthening precipitates during the high-temperature stress-relief process. However, elongation decreased relative to the As-built condition, which is interpreted to originate from increased localized deformation tendency caused by recovery and partial precipitation behavior.

In contrast, the LTSR condition exhibited relatively lower strength than the HTSR condition while maintaining more stable elongation behavior. This tendency is attributed to the substantial retention of the interdendritic Laves network under the low-temperature stress-relief condition, which suppressed excessive precipitation and localized precipitation coarsening.

After subsequent standard heat treatment, both the HTST and LTST conditions exhibited significant increases in strength under both room-temperature and elevated-temperature conditions. In particular, the HTST condition showed high yield strength and tensile strength owing to precipitation strengthening associated with the formation of γ' and γ'' strengthening precipitates. However, elongation decreased relatively. This behavior is closely associated with the coarse δ precipitation and localized precipitation concentration tendency observed in the SEM and TEM analyses. In particular, coarse δ precipitates concentrated along grain boundaries are considered to induce localized stress concentration, thereby limiting deformation capability.

In contrast, the LTST condition exhibited relatively higher tensile strength while maintaining an elongation comparable to that of the HTST condition. Rather than indicating a synergistic improvement in both strength and ductility, these results demonstrate that the LTST condition maintains a ductility level comparable to that of the HTST condition while providing a modest increase in tensile strength. In particular, under both room-temperature and elevated-temperature conditions, the LTST condition exhibited more uniform strain accommodation behavior, which is considered closely related to the uniformly distributed γ'/γ'' strengthening precipitates and fine δ precipitates.

When interpreted together with the TEM and EBSD results, the LTST condition preserved portions of the original interdendritic structure, resulting in more uniform distributions of fine γ'/γ'' precipitates and fine δ precipitates during subsequent aging treatment. In addition, relatively lower KAM values were observed under the LTST condition compared with the HTST condition, suggesting that the finely dispersed δ precipitates contributed to more stable relaxation of localized residual strain distribution.

Recent studies have demonstrated that the tensile properties of LPBF-fabricated Inconel 718 are governed by the combined contributions of γ'/γ'' precipitation, δ -phase evolution, and the associated microstructural stability rather than by a single strengthening mechanism. Consistent with this understanding, the observed tensile behavior in the LTST condition is interpreted as the combined result of the evolution of the γ'/γ'' strengthening precipitates together with the modified precipitation

pathway associated with the preserved interdendritic structure, rather than the strengthening effect of the δ precipitates alone. Consequently, the proposed LTSR strategy provides a modest increase in ultimate tensile strength while maintaining tensile properties comparable to those of the conventional HTST route. These findings indicate that the proposed LTSR strategy serves as an alternative precipitation-control approach through modification of the remaining interdendritic microstructure rather than providing universally superior mechanical performance [34–38].

Therefore, although the LTST condition exhibited a modest increase in ultimate tensile strength, the elevated-temperature yield strength and elongation were comparable to or slightly lower than those of the HTST condition at 649 °C. Therefore, the present results suggest that the primary role of the low-temperature stress-relief strategy is to tailor the subsequent precipitation pathway rather than to introduce a fundamentally different strengthening mechanism. These observations are also consistent with the relatively low and uniform KAM distribution observed in the EBSD analysis.

Nevertheless, a quantitative decomposition of the individual strengthening mechanisms was beyond the scope of the present study because quantitative precipitate statistics, including the size, volume fraction, and number density of the γ' , γ'' , and δ precipitates, were not available. Therefore, the strengthening behavior discussed herein is interpreted from the combined evidence obtained by the tensile, SEM, TEM, XRD, and EBSD analyses rather than from quantitative strengthening models. Future work incorporating quantitative precipitate characterization together with strengthening-model analysis will enable a more rigorous evaluation of the relative contributions of the individual strengthening mechanisms.

To further evaluate the significance of the proposed LTSR strategy, the tensile properties obtained in the present study were compared with representative post-processing routes for LPBF-fabricated Inconel 718 reported in the literature, as summarized in Fig. 11 and Table 6. The comparison includes representative solution-treated, direct-aged, HIP-assisted, and stress-relief-treated conditions reported for additively manufactured Inconel 718. Overall, the tensile properties obtained in the present study fall within the range reported in the literature at both room temperature and elevated temperature, providing a direct comparison with representative literature data.

The comparison presented in Fig. 11 and Table 6 indicates that the tensile properties achieved by the proposed LTSR strategy are generally comparable to those reported for representative post-processing routes. At room temperature, the LTST condition exhibited an ultimate tensile strength of 1416 MPa with an elongation of 23%, while at 649 °C a modest increase in ultimate tensile strength was obtained compared with the HTST condition, accompanied by slightly lower yield strength and elongation. These results suggest that the proposed LTSR strategy does not provide universally superior mechanical properties but instead offers a distinct precipitation-control approach through partial retention of the build-induced interdendritic Laves network, resulting in a different precipitation pathway from that of conventional HTSR-based processing.

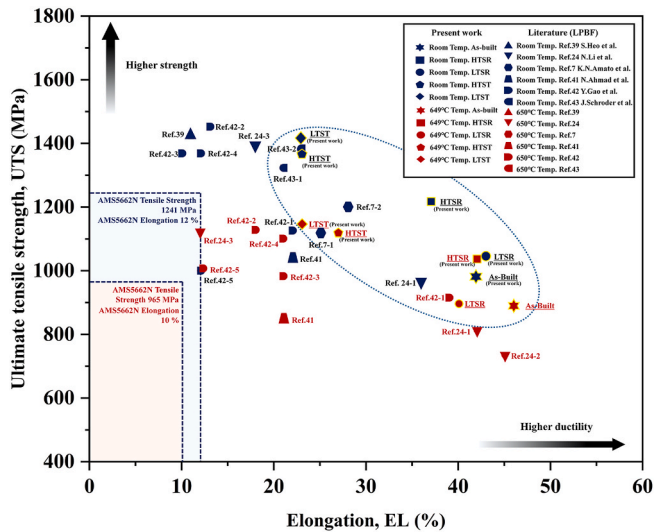


Fig. 11. Comparison of room-temperature and elevated-temperature tensile properties of LPBF-fabricated Inconel 718 reported in the literature and those obtained in the present study. Ultimate tensile strength (UTS) is plotted as a function of elongation for representative post-processing routes. The proposed LTST strategy exhibits tensile properties within the range reported in the literature while following a distinct precipitation pathway associated with partial retention of the residual Laves network.

3.6. Proposed mechanism of stress-relief-dependent precipitation evolution

Fig. 12 schematically illustrates the evolution of residual Laves networks and subsequent precipitation behavior according to different stress-relief strategies. In the conventional HTSR route, the build-induced fine Laves network rapidly decomposed during the high-

temperature stress-relief process at 1065 °C, resulting in early-stage Nb redistribution. Consequently, subsequent aging treatment promoted concentrated coarse δ precipitation along grain boundaries, while γ'/γ'' strengthening precipitates also exhibited relatively localized and heterogeneous distributions. This behavior is considered to originate from localized Nb redistribution following rapid homogenization, which subsequently induced heterogeneous precipitation behavior.

By comparison, under the proposed LTST route, the fine Laves network morphology formed in the As-built condition was largely retained during low-temperature stress-relief treatment at 550 °C. This behavior indicates that the residual Laves network remained as meta-stable Nb-rich regions without immediate homogenization.

During subsequent aging treatment, the retained Laves network is considered to have influenced the subsequent precipitation pathway through delayed Nb redistribution, resulting in comparatively finer and more uniform γ'/γ'' and δ precipitation behavior. Specifically, the LTST condition exhibited reduced coarse grain-boundary δ precipitation compared with the HTST condition, while fine dispersed δ precipitates were more uniformly distributed throughout the matrix. In addition, γ'/γ'' strengthening precipitates were formed more homogeneously within the matrix, resulting in relative suppression of localized precipitation concentration tendencies. EBSD analysis further revealed relatively lower KAM values under the LTST condition, which is considered closely associated with residual strain stabilization induced by uniform precipitation behavior.

Although direct quantification of Nb redistribution was not performed in the present study, comprehensive analyses based on SEM, XRD, TEM, and EBSD results suggest that the retained stability of the residual Laves network is likely to influence subsequent precipitation pathways. More importantly, the present findings suggest that the retained Laves network may influence the subsequent precipitation pathway in a manner consistent with delayed Nb redistribution, although this mechanism was not directly demonstrated in the present study. Further investigations based on STEM-EDS or atom probe

Table 6

Comparison of room-temperature and elevated-temperature tensile properties of LPBF-fabricated Inconel 718 processed using various post-processing routes reported in the literature and those obtained in the present study.

Ref.	Category	Manufacturing route	Post-processing route	RT UTS (MPa)	RT YS (MPa)	RT EL (%)	Test temperature	High-T UTS (MPa)	High-T YS (MPa)	High-T EL (%)
[39]	AM IN718	SLM	SA	1422	1236	11	650°C	1120	974	-
[24]	AM IN718	SLM	As-built	967	638	36	650°C	813	567	42
			Solution treatment	-	570	47		735	507	45
			Solution + double aging	1394	1229	18		1124	1025	12
[40]	AM IN718	WAAM	Standard aging	870	852	-	538°C	761	687	-
[7]	AM IN718	SLM	As-built	1120	830	25	-	-	-	-
		SLM + HIP	982°C SR/ HIP	1200	890	28	-	-	-	-
[41]	AM IN718	LP-DED	1065°C / 1.5 h	1040	950	22	650°C	850	760	21
			1065°C / 1 h + 760°C / 10 h + 650°C / 10 h							
[42]	AM IN718	SLM	As-built	1126	677	22	650°C	914	677	39
			SHT980/ DA	1453	914	13		1126	914	18
			SHT980/ DA	1370	773	10		982	773	21
			SHT1080/980 + DA	1371	916	12		1099	916	21
			(AMS 5662)	1000	862	12		1000	677	12
[43]	AM IN718	Wrought	Direct Aging (DA)	1325	1120	21	-	-	-	-
		SLM	Full Heat Treatment (FHT)	1380	1085	23	-	-	-	-
		SLM								
Present study	AM IN718	As-built	LPBF	980	629	42	649°C	889	668	46
		HTSR	LPBF/ 1065°C SR	1217	961	37		1039	825	42
		LTST	LPBF/ 550°C SR	1044	735	43		898	686	40
		HTST	LPBF/ HTSR/ ST/ aging	1370	1199	23		1118	1005	27
		LTST	LPBF/ LTST/ ST/ aging	1416	1175	23		1147	979	23

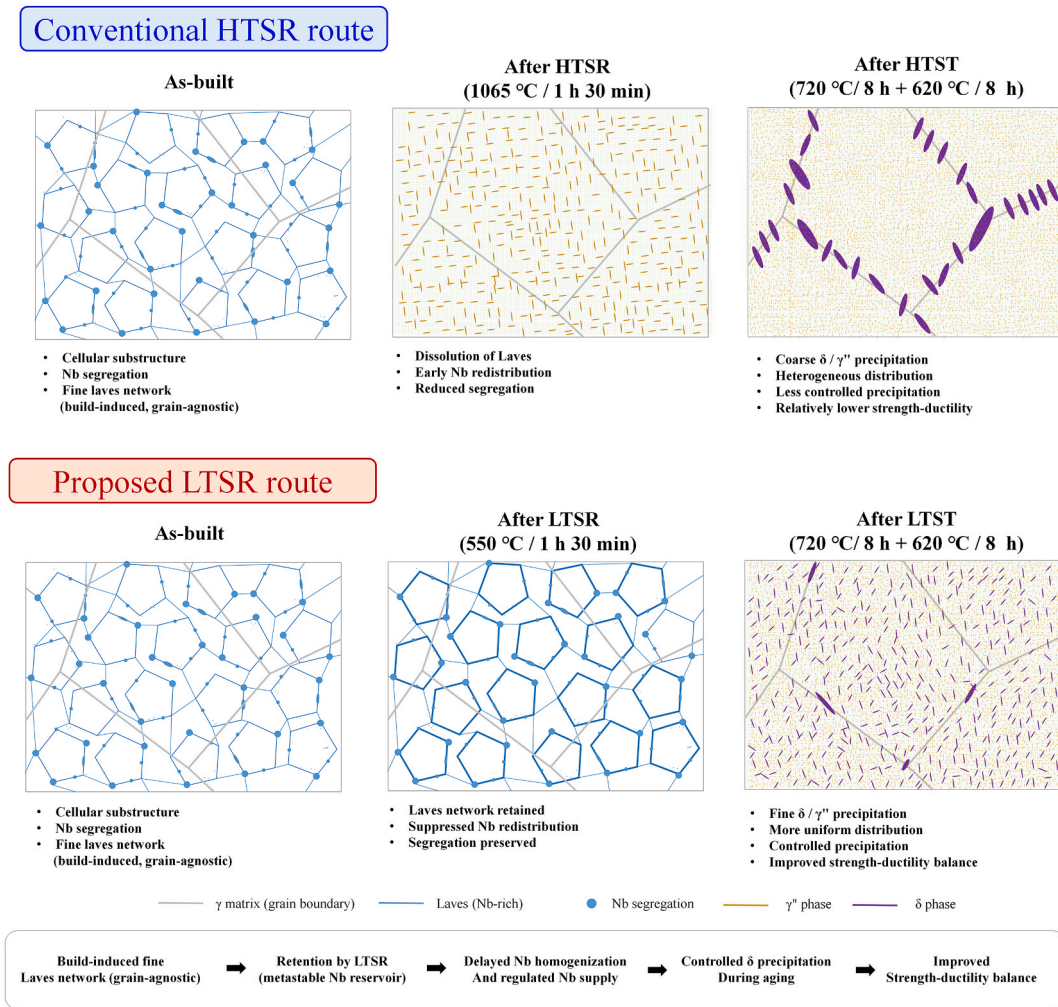


Fig. 12. Proposed mechanism of stress-relief-dependent precipitation evolution in LPBF-fabricated Inconel 718 comparing the conventional HTSR route and the proposed LTSR route, illustrating residual Laves network evolution, Nb redistribution behavior, precipitation morphology, and corresponding strength–ductility response.

tomography (APT) are required to quantitatively clarify localized Nb redistribution behavior around the retained Laves network.

Therefore, the low-temperature stress-relief-based LTSR strategy is considered a promising post-processing approach capable of utilizing interdendritic Laves networks to tailor precipitation evolution. Furthermore, the uniform dispersion of γ'/γ'' strengthening precipitates and fine δ precipitates achieved under the LTSR route suggests the potential to realize more stable tensile deformation behavior together with an improved balance of mechanical properties compared with conventional HTSR-based processing routes.

4. Conclusion

In the present study, the effects of conventional high-temperature stress relief (HTSR) and the proposed low-temperature stress relief (LTSR) strategy on residual Laves evolution, precipitation behavior, and mechanical properties of LPBF-fabricated Inconel 718 were systematically investigated. The main findings are summarized as follows:

- In the As-built condition, a build-induced fine Laves network was formed along the interdendritic regions. Under the HTSR condition, the residual network rapidly collapsed owing to rapid homogenization behavior, whereas the LTSR condition retained a significant portion of the original fine Laves morphology.

- After subsequent aging treatment, the HTST condition exhibited dominant coarse grain-boundary δ precipitation, whereas the LTST condition showed more uniformly distributed fine dispersed δ precipitates. In addition, γ'/γ'' strengthening precipitates in the LTST condition were more homogeneously distributed throughout the matrix.
- EBSD analysis revealed that the LTST condition exhibited relatively lower KAM values compared with the HTST condition, which is considered to be associated with residual strain stabilization induced by the fine and uniform precipitation morphology. In contrast, differences in overall grain morphology remained relatively limited, suggesting that the mechanical property variations observed in this study were more strongly related to changes in precipitation pathways than to grain-growth behavior.
- Tensile tests demonstrated that the LTST condition exhibited a modest increase in ultimate tensile strength compared with the HTST condition. At 649 °C, however, this increase was accompanied by a slight reduction in yield strength and tensile ductility. The observed tensile behavior is interpreted as the combined result of the modified precipitation pathway together with the evolution of the γ'/γ'' strengthening precipitates, while the fine δ precipitates are considered to contribute primarily to precipitation morphology and grain-boundary stability rather than serving as the principal strengthening phase.

Therefore, the present study suggests that the remaining interdendritic structure may influence the subsequent precipitation pathway and microstructural stability. Although direct quantification of Nb redistribution was beyond the scope of the present study, the observed microstructural evolution is consistent with delayed Nb redistribution associated with the preserved interdendritic structure.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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