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Acknowledgments

The authors gratefully acknowledge the support of NASA Aeronautics Research Mission Directorate and the Transformational Tools and Technologies (TTT) Project. The authors thank Drew Davidson of the NASA Glenn HX5 group for his careful metallographic preparation work, and Dr. Peter Caltagirone for reviewing the manuscript.

This work was sponsored by the
Transformative Aeronautics Concepts Program.

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Summary

Lattice block structures made up of high-temperature superalloys could offer advantages in density, efficiency, and tailored properties. Three candidate lattice designs were screened through additive manufacturing of superalloy 718. Laser powder bed fusion was applied with 718 powder to produce lattice blocks for three-dimensional octahedral unit-cell designs of three heights. Properties of structural designs versus additively manufactured 718 lattices were compared, including structural dimensions, densities, defects, grain structures, crystallographic texture, and surface residual stresses. Manufactured lattice I diverged the most from its structural design, with both corner and center nodes merged into continuous columns. Manufactured lattice III came closest to its design, though the actual nodes and struts were still larger in cross section than in the design. Only modest grain coarsening and negligible chemical segregation were observed for all three designs, suggesting uniform thermophysical and mechanical properties are possible. Significant tensile residual stresses were present at the surface of the manufactured blocks, with highest stresses in the building direction. Current findings indicate this concept could produce useful superalloy structures for high-temperature-capable static components requiring tailored density, and thermophysical and mechanical properties.

Introduction

Concepts for cellular and lattice block metal alloy structures have been considered for decades (Refs. 1 to 10). In adapting natural and manufactured cellular material concepts to metal alloys, weight density can

be directly decreased with increasing void content. Beyond this fundamental property, stiffness, thermophysical, electrical, and mechanical properties can also be altered with respect to fully dense baseline structures for improving efficiency in meeting application requirements. In some cases, these lattice structure properties can be selectively engineered to be either isotropic or anisotropic for enhanced tailoring to applications. Innovative designs have been generated to target numerous applications in power generation, transportation, aeronautics, space, and medical fields. General governing equations have been recently reviewed for physical, thermophysical, electrical, and mechanical properties (Refs. 4 and 10).

The benefits of cellular and lattice block metal alloy structures can be extended to metallic materials designed for applications at elevated temperatures. Nickel-based superalloys as a class can be used to high fractions of their melting temperature (Ref. 2) and hence offer attractive candidates for cellular and lattice block structures (Refs. 3 and 5). Superalloy 718 (“718”) is a well-known material that has been used in a very wide range of applications in the oil and gas extraction, power generation, and aerospace propulsion fields (Ref. 11), for temperatures up to 700 °C. For over 40 years, 718 has been commercially produced via cast plus wrought processing, with several subsequent heat treatment paths developed for different commercial applications. For these reasons, 718 is of high interest for evaluations of lattice block structures.

In experimental adaptations of 718 to these structures, the material processing path has been a rate-limiting consideration for resulting properties and potential commercialization. Several general paths have been explored. Approaches using investment casting of 718 have shown good progress in producing lattice block (Refs. 5 and 12) structures. In this approach, a lost wax pattern is inserted in the cross section to mimic the solidified structure, after which the pattern is evaporated by later heating steps. Studies have shown promising combinations of reduced density and good compressive strength; however, processing challenges with wax pattern making, the die fill, casting defects, and excess metal were identified.

Additive manufacturing (AM) has been investigated for producing cell and lattice structures for various classes of alloys over the last two decades (Ref. 9). This path allows very high flexibility in layered designs of cells and lattices that can be highly refined for targeted applications (Ref. 10). Since 718 has also been adapted using powder processing combined with additive manufacturing processes (Ref. 13), multiple studies have utilized additive manufacturing by laser powder bed fusion to produce 718 lattice block (Ref. 14) and cellular (Ref. 15) structures.

The objective of the present study was to assess additively manufactured 718 lattice blocks of several designs for consistency of structural dimensions and configuration as well as their manufactured densities, defects, grain structures, crystallographic texture, and surface residual stresses. The goal was to determine if this design-processing path was potentially adaptable for tailored high-temperature applications.

Materials and Procedures

For these screening trials, three-dimensional (3D) octahedral unit cell designs I, II, and III were generated with increasing height in the building direction, as shown in Figure 1. Design nodes had a fixed square side spacing in the x-y plane of 500 μm , and height spacings of 400 μm (I), 600 μm (II), and 700 μm (III) in the building direction. From the lattice block parameters, three pairs of lattice blocks were additively manufactured on a single build using 718 powder, as shown in Figure 2. To accomplish this, argon-atomized 718 powder was screened to –230 mesh and a laser powder bed fusion technique using an EOS M100 at the NASA Glenn Research center was used for the build. This system used a build plate of 304 stainless steel to repetitively add 20- μm -thick layers in a controlled argon atmosphere containing roughly 0.1% O_2 .

The blocks were removed from the build plate using electrical discharge machining (EDM), and all were examined in the as-built state. One block “b” of each design was retained at full dimensions, while the other block “a” was sectioned as shown in Figure 3 using an abrasive disk saw. Various sections were used for density, residual stress, and computed tomography (CT) measurements, and others were polished for metallographic evaluations. Density was measured by weighing the largest sections of each design and measuring their outer dimensions.

Residual stresses were measured at the surfaces of these blocks using a Bruker D8 Discover (area detector) x-ray diffractometer aligned in accordance with the approach and error bounds specified in ASTM E 915-10, here applied to the side-inclination rather than iso-inclination method. Data were gathered using Mn K α radiation and the (311) crystallographic plane on a specimen target area of 16 mm². Each residual stress dataset consisted of 24 area detector frames taken at 4 sample tilt (psi) angles (0°, 15°, 30° and 45°) and 6 sample rotation (phi) angles (0°, 45°, 90°, 180°, 225°, and 270°). Sample X-ray penetration depths decrease with increasing psi angle for a solid surface, ranging from an estimated depth near 19 μ m to 13 μ m, which corresponds to a 99% contribution to the diffracted beam on a flat solid surface. These x-ray results were analyzed using the Bruker LEPTOS v.7 software. Surface residual stresses were measured on the front and back broad faces of each block at the geometric center, 10 mm up from the center, and 10 mm down from the center, as depicted in Figure 4.

CT of the sections in Figure 3 (labelled “CT”) was performed on a 225 Kv Microfocus CT, and the acquired data were analyzed using North Star Imaging efX-CT 3D visualization software. Microstructures were examined on metallographic sections prepared parallel and transverse to the vertical building direction, B. Samples were mounted in PolyFast™ (Struers ApS) and conventionally polished using successively finer SiC grit polishing paper followed by vibratory polishing in a 0.05- μ m-colloidal silica slurry. Optical and scanning electron microscopy (SEM) were employed to examine grain microstructures. Microstructures of metallographically prepared specimen sections were evaluated using a Hitachi 4700 field emission scanning electron microscope (FESEM) operated at 15 kV and 15 μ A with an integrated Oxford energy dispersive spectroscopy system. Further evaluations of microstructure with accompanying electron backscatter diffraction (EBSD) were performed on a Tescan MAIA3 field emission scanning electron microscope operated at 20 kV accelerating voltage with an integrated Oxford energy dispersive spectroscopy system. Aztec software was used to collect and analyze the EBSD data, with step sizes of 5 μ m at a magnification of 250 $\times$ and 1 μ m at 1,000 $\times$.

Crystallographic texture was measured on the largest square polished longitudinal sections using a Malvern Panalytical Empyrean X-ray diffractometer. Experimental data were gathered using Co-K α radiation for the (111), (200), (220), and (311) poles using a 2.0-mm (h) by 0.5-mm (w) beam size in conjunction with a 0.27° parallel plate collimator and a scintillation detector. Analysis was performed with the Malvern Panalytical *Texture* software package to calculate the orientation distribution function (ODF). This, in turn, was used to produce corresponding “Calculated” full pole figures for the (200), (220), and (111) poles.

Results

Macroscopic images of the blocks after removal from the build plate are shown in Figure 2. Measured densities are compared in Figure 5. Measured densities of the manufactured lattice blocks are about 50% lower than the reported solid density for 718 (Ref. 16) of 8.193 g/cm³ (0.296 lb/in³). The lowest density was measured for lattice block III, consistent with its greatest design node height. Yet, the differences in densities for lattice blocks I, II, and III are quite modest.

Typical optical and SEM images of the lattice broad sides at higher magnifications are shown in Figure 6 and Figure 7, respectively. Consistent surface node spacing was evident for all three manufactured lattices, and the node spacing in the building direction appeared to increase (comparing blocks I, II, and III) as expected from the design. However, both the nodes and the struts had greater visual cross sections than depicted in the designs. The nodal shape appeared increasingly distorted in scanning from lattice block I to blocks II and III. Finally, small powder particles were adhered to the surfaces for all three lattices, indicating incomplete melting of the powder. These small powder particles were also visible in the windows between the nodes, beneath the outer surface.

CT enabled assessments of the node spacing, strut length, and powder particles throughout the scanned volumes of the CT sections from lattice blocks Ia, IIa, and IIIa depicted in Figure 3. The CT volumes for each manufactured lattice are compared in Figure 8. Interior transverse planes sectioning the corner nodes, intermediate struts, and center nodes are shown in Figure 9 to Figure 11. Although the node spacings in the transverse planes were unchanged in the lattice designs, there were clear differences in node spacings between the manufactured lattice blocks. For lattice block Ia, the corner nodes in Figure 9(a) and center nodes in Figure 9(c) were interconnected across the diagonal directions in these transverse planes. Only a few of these nodes were interconnected in this way for the equivalent transverse planes of lattice block IIa in Figure 10, and none were continuously interconnected for these transverse planes of lattice block IIIa in Figure 11. For all three lattice blocks, pores and small adhered but unmelted powder particles were evident at the corner nodes, center nodes, and intermediate struts.

Additional CT analysis was completed using interior planes oriented parallel to the building direction. These planes sectioned portions of the scan, bisecting the corner nodes, intermediate struts, and center nodes of the CT volumes, which are shown in Figure 12 to Figure 14. The most striking difference here was observed for block Ia shown in Figure 12. The corner nodes and the center nodes were each completely merged into continuous columns, whereas the intermediate struts adjacent to the corner nodes were partly merged. However, the intermediate struts had a continuous gap adjacent to each center node. These interior planes parallel to the building direction of block IIIa in Figure 14 displayed the other extreme, with separated corner and center nodes elongated in the building direction, and intermediate struts arranged in discontinuous “X” rows and columns. The equivalent planes for block IIa of Figure 13 displayed intermediate response for the nodes and intermediate struts. The node spacing in the building direction did increase as intended throughout the volumes in comparing lattice blocks IIa and IIIa. Pores and small adhered powder particles were again evident in the struts and nodes of all three lattice blocks.

It was not possible to locate the true metallographic sections to consistently and precisely intersect the centers of the nodes or intermediate struts for each block. However, the characterization of metallographic sections oriented as shown in Figure 4 still allowed assessments of microstructures and defects associated with node spacing, adhered powder particles, and porosity. Sections prepared transverse to the building direction are compared in the optical and SEM images of Figure 15 and Figure 16, respectively. Pores having diameters up to about 50 μm were evident in sections of all three sectioned lattice blocks.

The SEM micrographs of Figure 16 displayed elongation of some grains in the strut directions. This was confirmed using EBSD, with the generated maps shown in Figure 17. Sections of lattice blocks Ia, IIa, and IIIa all displayed some grains (E) elongated in the strut directions, with lengths up to 100 μm and widths of 4 to 50 μm . These were accompanied by scattered colonies (C) of smaller, more equiaxed grains typically at 5 to 20 μm in diameter. The corresponding inverse pole figures from EBSD for these locations are compared in Figure 18. The lower pole figures generated at high magnification did not conclusively show strong texture, perhaps partly because of an insufficient number of grains being analyzed. The upper {100} pole figures generated at lower magnification for the lattice blocks indicated no significant texture, with mixed colonies of small grains (C) and the large grains (E) elongated in the

“X” pattern of the struts. These pole figures were not clearly consistent across the three lattice blocks. Energy dispersive x-ray spectroscopy (EDS) analysis maps were also inspected over these same image fields, as shown in Figure 19. These sections of lattice blocks Ia, IIa, and IIIa all displayed surprisingly uniform composition, with only very minor segregation of Nb and Mo at second phase (delta) features.

Sections prepared across the thickness that were parallel to the building direction are compared in the optical images of Figure 20. Pores were also evident in these sections for all three lattice block designs. The SEM images of these sections shown in Figure 21 suggested lower frequency of elongated grains in this plane than for the transverse plane. This was confirmed in the EBSD images shown in Figure 22. The grain dimensions were comparable to those measured in the transverse sections, though with fewer grains elongated in the building direction on this plane. The corresponding inverse pole figures from EBSD for these locations are compared in Figure 23. The pole figures generated at high magnification also had a low number of grains being analyzed. These pole figures generated at low and high magnifications did not show a conclusive strong texture in these sections. Only minor, localized segregation of Mo and Nb was apparent in the EDS maps of Figure 24 for each of these sections, with no linear dendritic segregation apparent.

Optical images for the large-area metallographic sections of Figure 4, prepared for X-ray assessments of texture parallel to the building and width directions, are shown for lattice blocks Ia, IIa, and IIIa in Figure 25. Typical SEM images, EBSD images, and pole figures of the large-area longitudinal-width metallographic sections prepared for lattice blocks Ia, IIa, and IIIa are shown in Figure 26 to Figure 28. These images suggested the lowest SEM magnification of 50× clearly sampled more grains than before. Although the pole figures had modest evidence of [001] fiber texture, this only occurred at very low multiples of uniform density (MUD).

X-ray diffraction allowed assessing texture across the entire surface of these large-area metallographic sections. The results for X-ray evaluations of crystallographic texture as measured across these entire metallographic sections are compared in Figure 29 to Figure 31. It can be seen from these pole figures that there is no significant crystallographic texture on the macroscopic scale of these samples. Consequently, the visible elongated, consistently aligned grains noted in earlier figures were outnumbered by smaller equiaxed grains.

X-ray diffraction was also used to measure residual stresses at the surface on the broad faces, averaged across each depicted square at locations U, C, and D in Figure 4 on each side of each lattice block. Note that bottom sections 9 mm in height had been trimmed from lattice blocks Ia, IIa, and IIIa before these residual stress measurements. The residual stresses are compared in Figure 32. For each lattice specimen, no significant differences were detected between locations U, C, and D and between the front and back block faces for each direction. Trimming the indicated bottom sections (shown in Figure 4) off from blocks Ia, IIa, and IIIa also did not induce a significant redistribution in residual stresses at the locations measured. Substantial tensile residual stresses near 100 MPa were measured in the building direction for each lattice block, while the stresses measured transverse to the building direction were slightly compressive at –10 to –40 MPa. One-way analysis of variances indicated that block I had significantly greater mean tensile residual stress S22 in the building direction and significantly greater mean compressive residual stress S11 transverse to the building direction, compared to those of blocks II and III. The tensile residual stress S22 in the building direction progressively decreased for blocks I, II, and III, as shown in Figure 32. Mean in-plane shear stress S12 was not significantly different between blocks I, II, and III.

Discussion

The manufactured nodes and the struts had greater volumes than intended in all three of the lattice designs. The merging of the nodes for lattice blocks Ia and Ib presented the extreme outcome of this increased volume. One can postulate that the layer thickness and the melt pool area and depth were larger than the designed node and strut volume. Single-track experiments (Ref. 17) could help shed light on this aspect; however, heat buildup and transfer for each layer in these lattice configurations would bring additional complications, requiring tailored time-dependent heat transfer modeling to understand. Porosity and adherence of small powder particles of the manufactured lattices were like those observed in many other additively manufactured volumes and surfaces (Ref. 13) produced from laser powder bed fusion of superalloy 718. The inherent multiplicity of surfaces produced in a designed lattice propagated the adhered powder particles through the structures here. Despite these defects, from a practical engineering point of view, the consistency of structure in each block suggested potential lattice designs could still be useful structures for components requiring tailored densities and thermophysical and mechanical properties. Although not intentionally designed, the columnar merging of corner and center nodes for lattice block I could even offer higher strength in the building (column) direction than designed. The present lattice blocks were not deemed suitable for mechanical testing because of their nodular faces. However, this could be accommodated by including solid faces on at least two opposing sides in future designs.

Although some grains displayed directional coarsening, these grains were not strongly aligned in the building direction and not as predominant as often reported in the literature for solid sections of additively manufactured superalloys, including 718 (Ref. 13). Dendritic chemical segregation was also not observed in these lattice blocks as was reported for solid sections of this superalloy (Ref. 13). Evidently, these lattice structures in additive manufacturing acted to impede or break up each of these features, which can produce anisotropy in thermal and physical properties. This was the case even for lattice block design I, where merging of corner nodes and center nodes occurred during manufacturing. These aspects are promising for structural design of these lattices, suppressing complications of composition-driven location-specific properties and texture-driven directional thermal and physical properties.

Potential refinements in design and additive manufacturing of these lattices could influence the above aspects. An increased geometric scale of the designed lattices and variations in laser powder bed fusion conditions could improve the agreement between designed and manufactured dimensions of nodes and struts as well as aid in improving the content of porosity and adhered powder particles. To help improve mechanical performance, heat treatments could be conducted to precipitation harden the microstructure and relax residual stresses of manufactured lattice blocks. However, this would require trials to assess structural distortion versus improved precipitation and stress relief in the lattices. If there is a need to close the pores within struts and nodes, direct hot isostatic pressurization at elevated temperatures could also be employed, although this further increases the risk of distorting the designed lattice structure and would require careful experimentation.

Potential applications of such superalloy lattice block structures could include traditional high-temperature load-bearing components that require high durability with low density (Ref. 14). This could extend to applications that would benefit from tailored, direction-dependent elastic properties, expansion properties, and permeability (Ref. 15). Thermal energy conversion applications, including heat exchangers, heat sinks, and heat pipes, could also be considered (Ref. 18), possibly with tailored anisotropic thermal and fluid flow properties.

Summary and Conclusions

Several candidate lattice designs were screened through additive manufacturing of superalloy 718. Laser powder bed fusion was applied with 718 powder to produce lattice blocks having three-dimensional octahedral unit cell designs of several heights. Comparisons of manufactured versus as-designed 718 lattice structures indicated lattice I diverged the most from its intended design, with both corner and center nodes merged into continuous columns. Manufactured lattice III came closest to its intended design, though the actual nodes and struts were still larger in cross section than for the design. Only modest grain coarsening and chemical segregation were observed for all three designs, suggesting uniform thermophysical and mechanical properties could be possible. Significant tensile residual stresses were present at the surface of the manufactured blocks, which were highest in the building direction for lattice design I.

It can be concluded that

1. Significant reductions in part density can be attained using additive manufacturing with lattice block designs.
2. Such lattice block designs will need to account for additive manufacturing processes, including melt pool dimensions and heat transfer during laser scanning.
3. The lattice structure can help deter [001] directional grain growth, associated texture, and anisotropic properties with respect to the building direction that is often observed in additive manufacturing of many alloys.
4. The lattice structure can also be used to minimize dendritic chemical segregation in additively manufactured parts.
5. Significant residual stresses can be generated in additively manufactured lattice blocks, even when no significant distortion is observed.
6. Current findings indicate additive manufacturing has good potential to produce useful superalloy lattice block structures for high-temperature-capable static components requiring structurally tailored density and thermophysical and mechanical properties.

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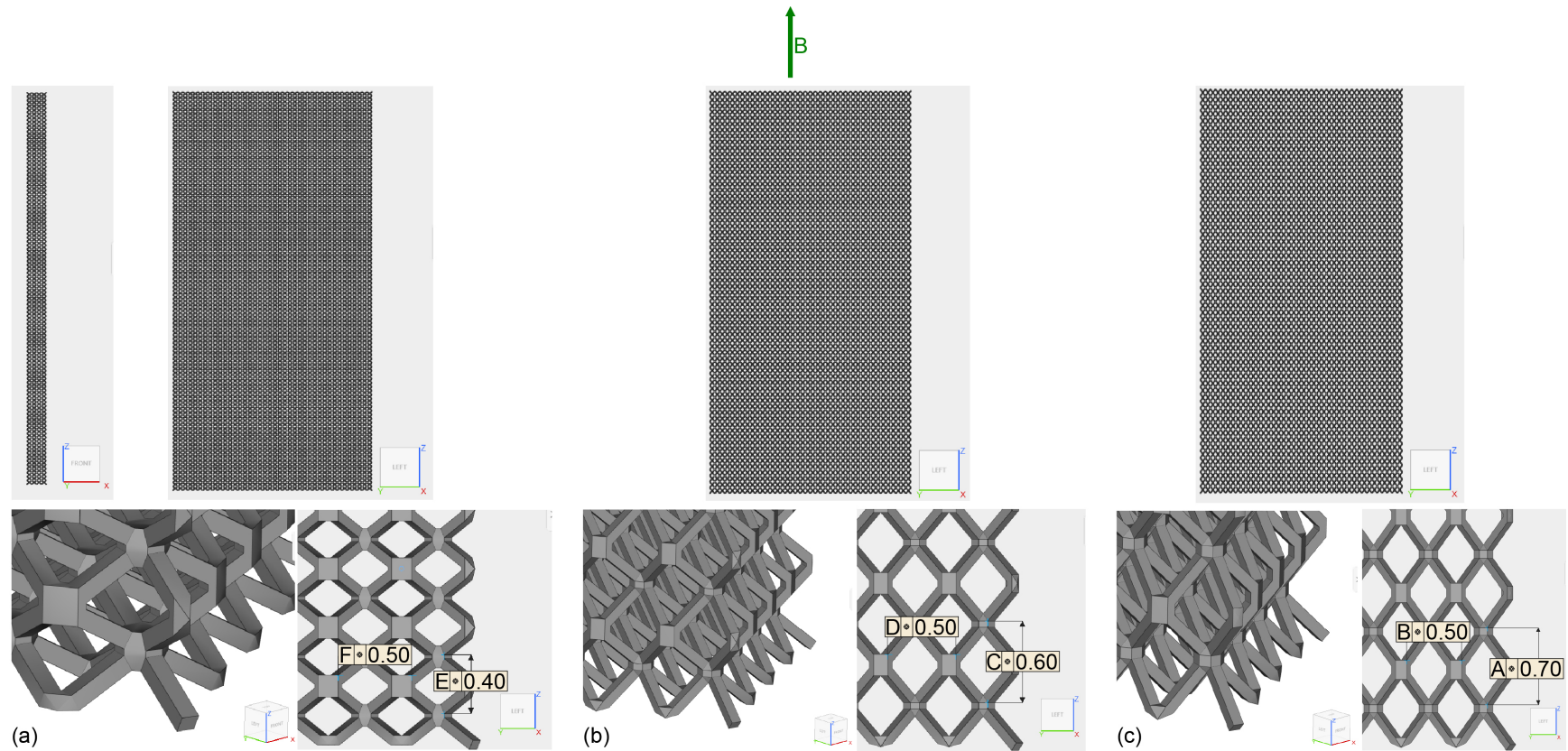


Figure 1.—Octahedral unit cell designs with increasing height in the vertical building (B) direction. Dimensions are in millimeters. (a) I. (b) II. (c) III.

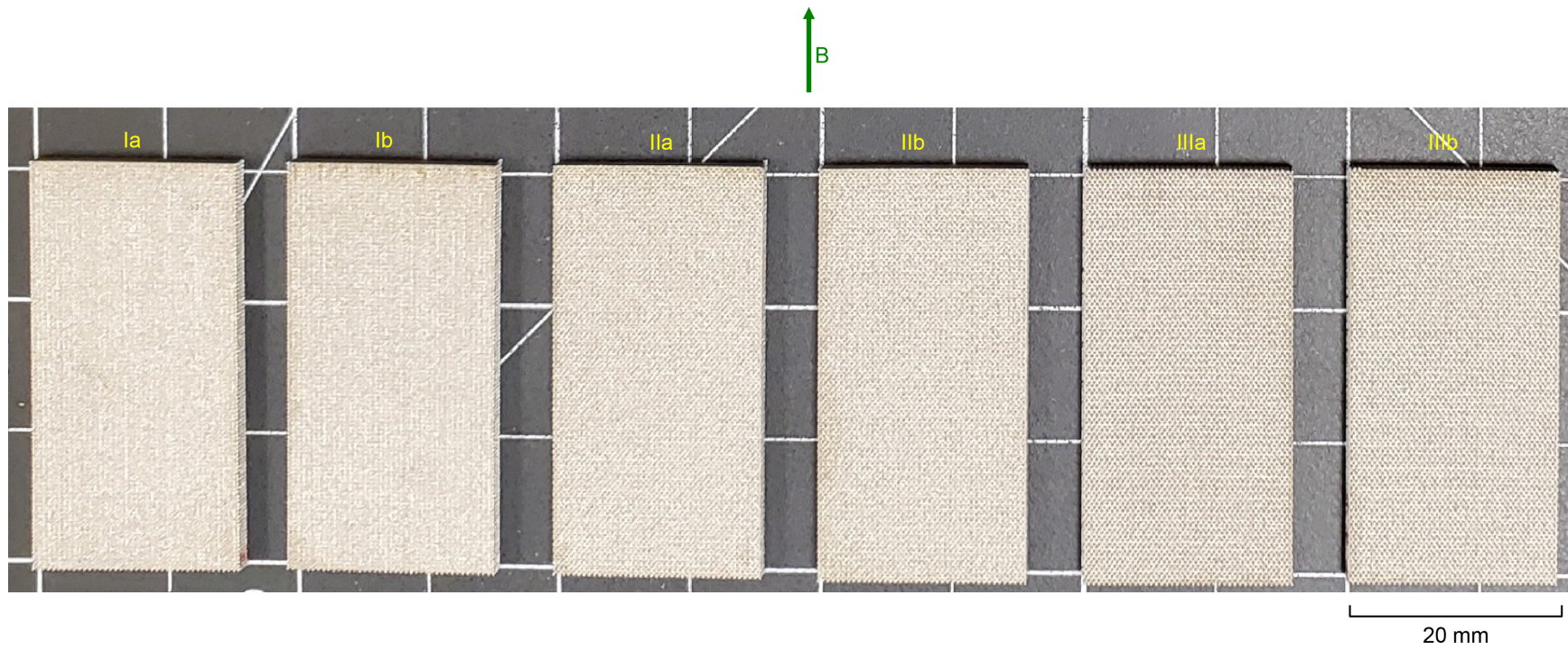


Figure 2.—Optical images of completed duplicate lattice blocks a and b for designs I, II, and III. The building (B) direction is oriented vertically.

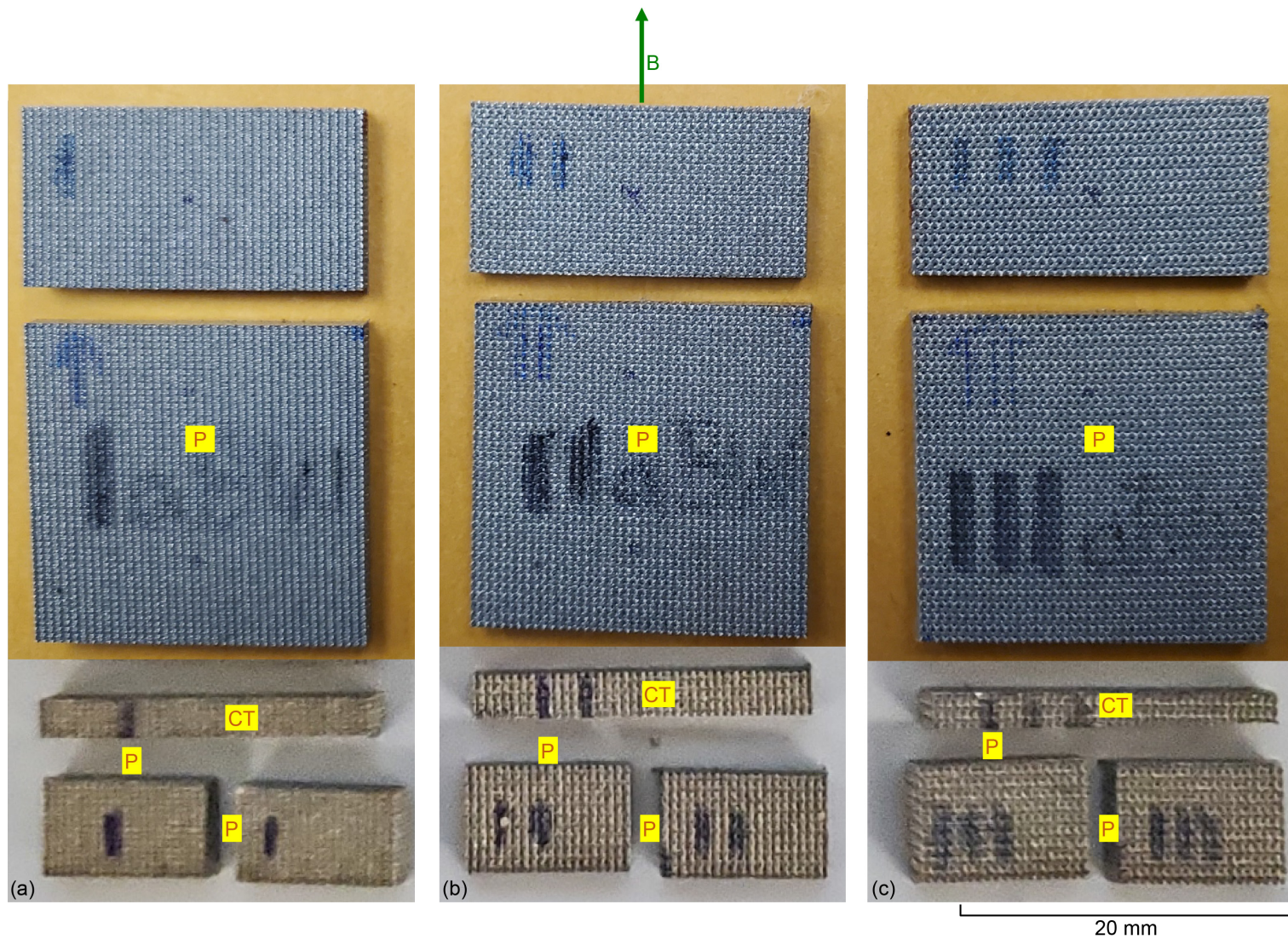


Figure 3.—Sections extracted from block “a” of lattice. P = metallographically mounted plus polished surfaces, CT = section for computed tomography. The building (B) direction is oriented vertically. (a) Design I. (b) Design II. (c) Design III.

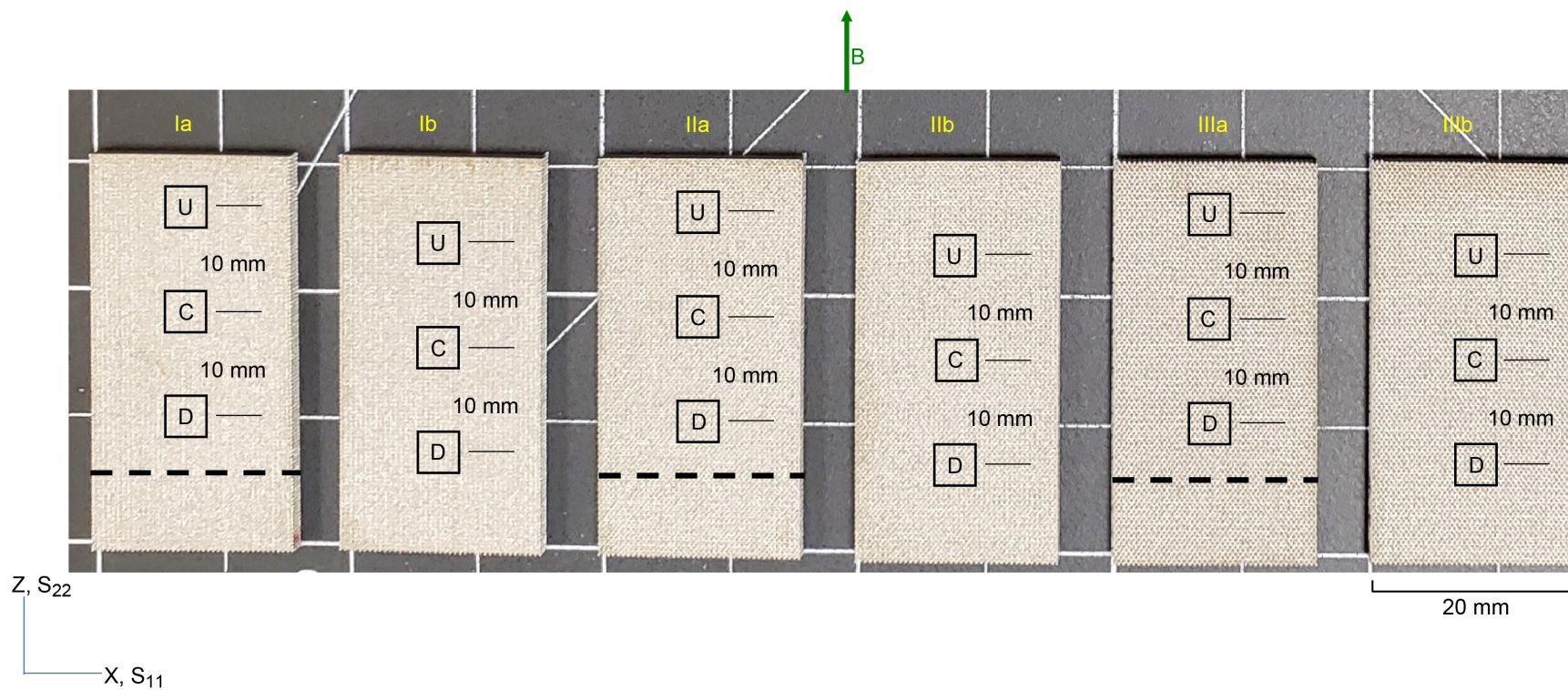


Figure 4.—Optical images showing consistently spaced 4 mm x 4 mm square areas scanned by x-ray diffraction for average residual stress on both the front and back faces of each lattice block. The building (B) direction is oriented vertically. Note the bottom sections of blocks Ia, IIa, and IIIa had been removed where indicated (- -) before these measurements.

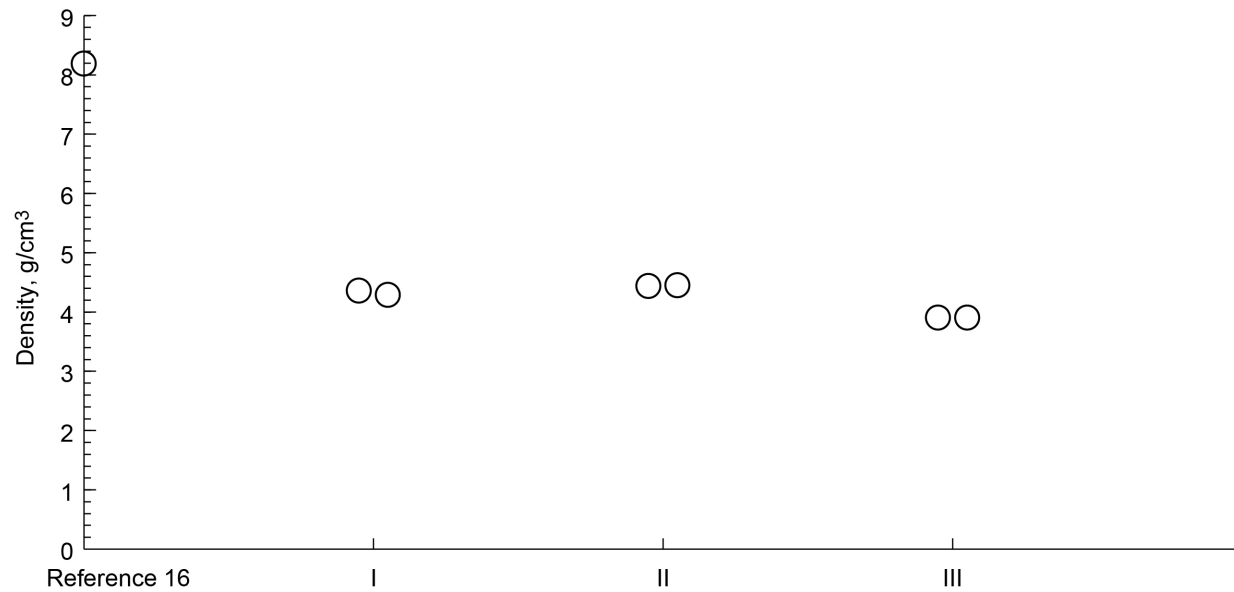


Figure 5.—Comparison of densities measured for lattice blocks a and b of designs I, II, and III as shown in Figure 4 with density of 718 reported in Reference 16.

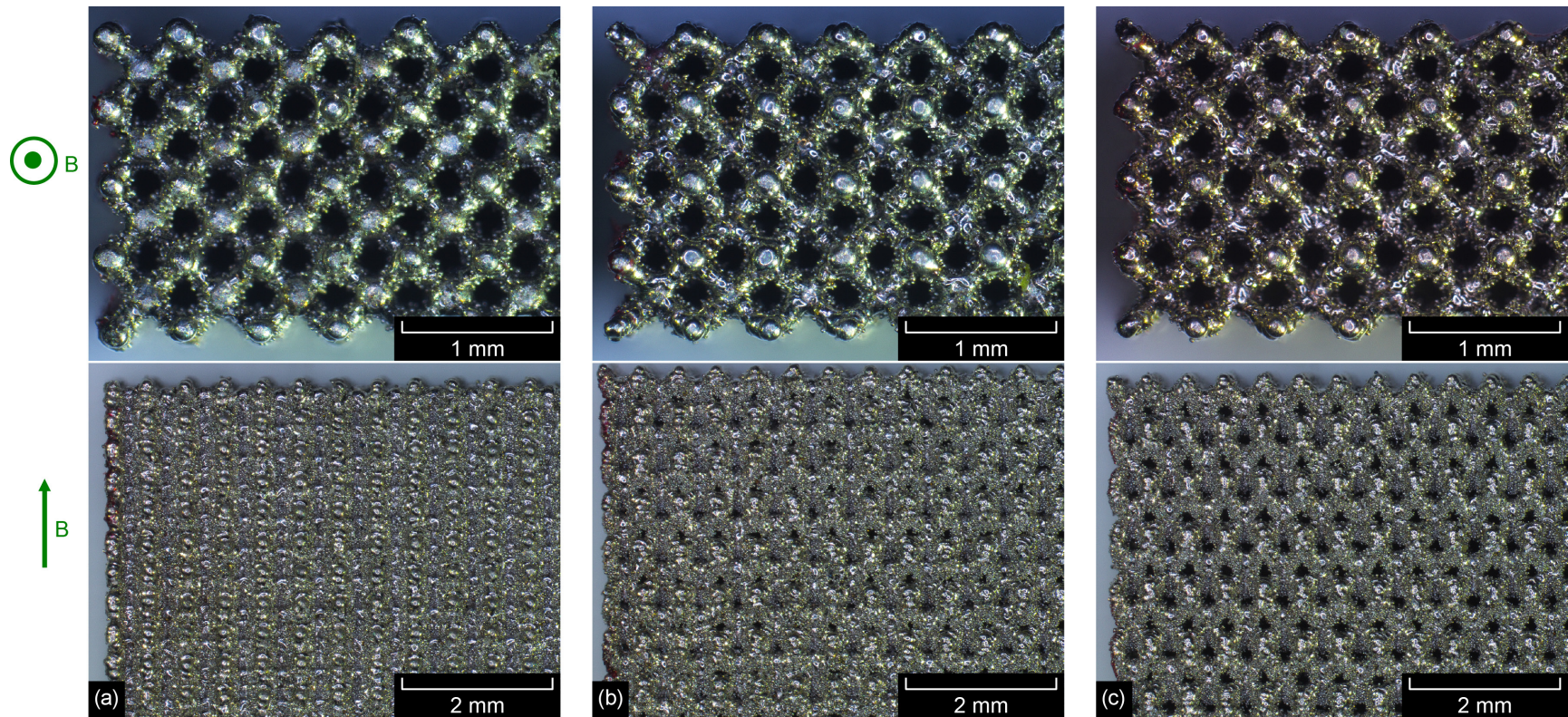


Figure 6.—Optical images showing typical top and side views of completed lattice blocks. The building (B) direction is shown. (a) Design I. (b) Design II. (c) Design III.

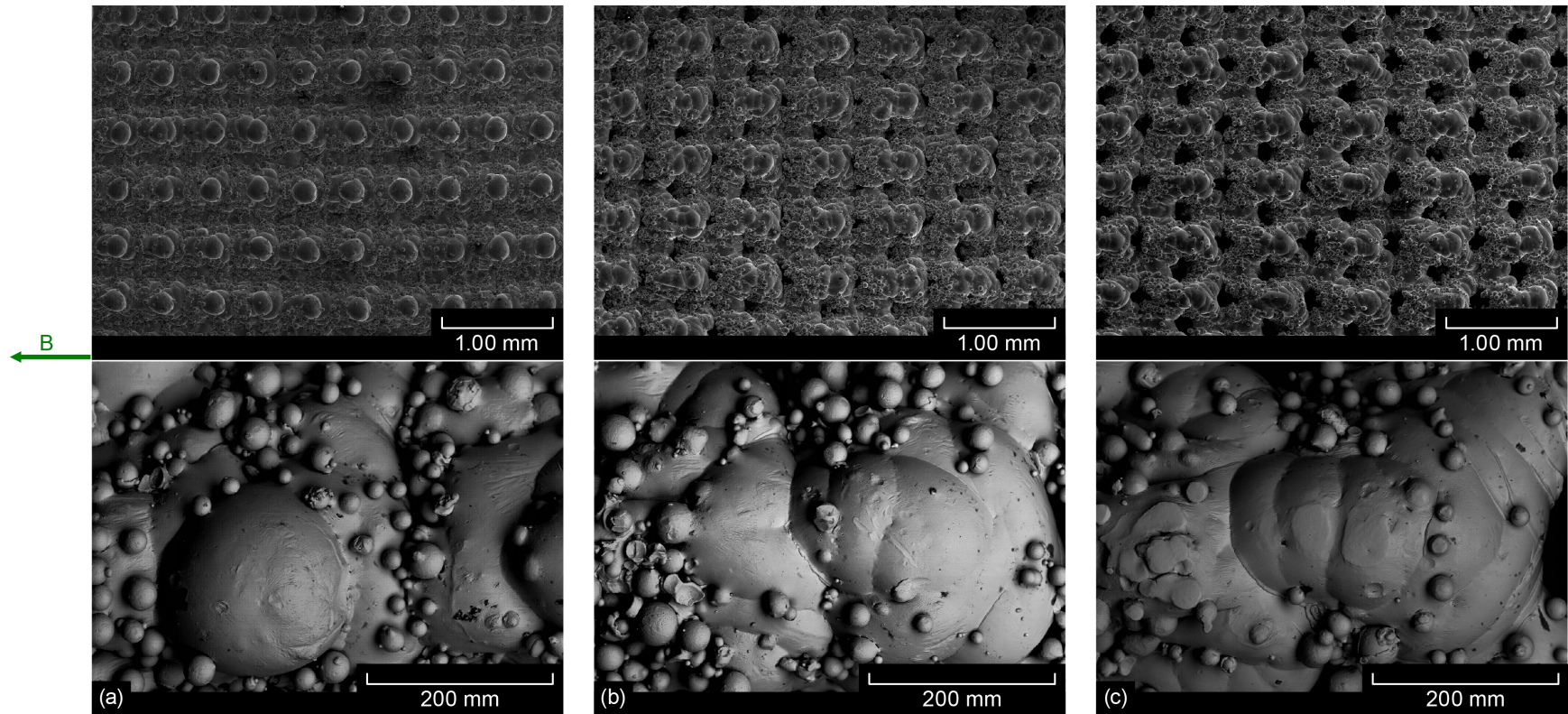


Figure 7.—Typical SEM images from the center of broad sides showing details of completed lattice blocks. The building (B) direction is horizontal. (a) Design I. (b) Design II. (c) Design III.

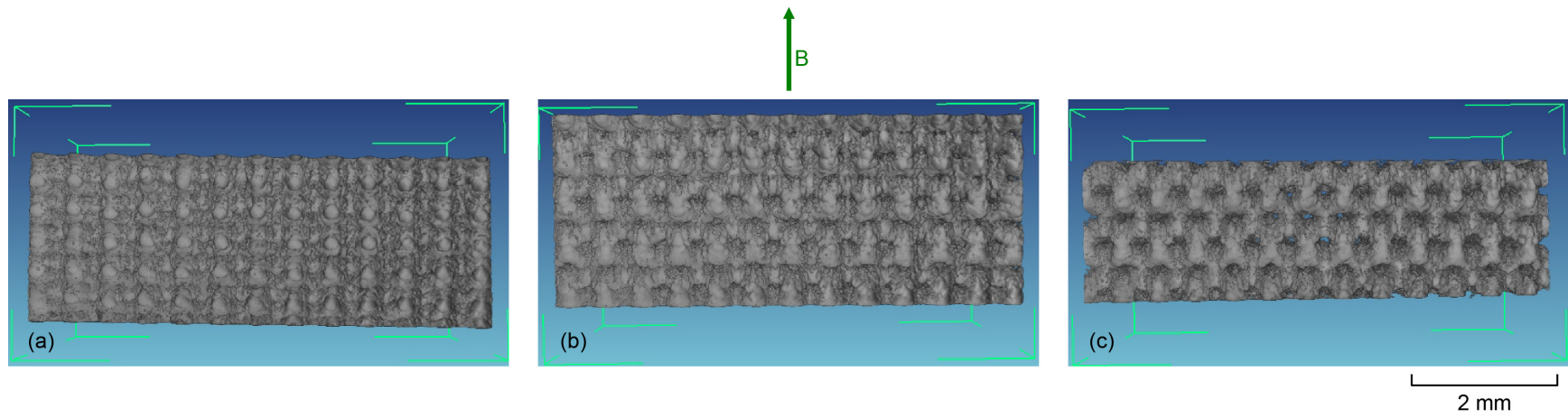


Figure 8.—The side view of CT volumes measured for lattice blocks. The building (B) direction is oriented vertically. (a) Ia. (b) IIa. (c) IIIa.

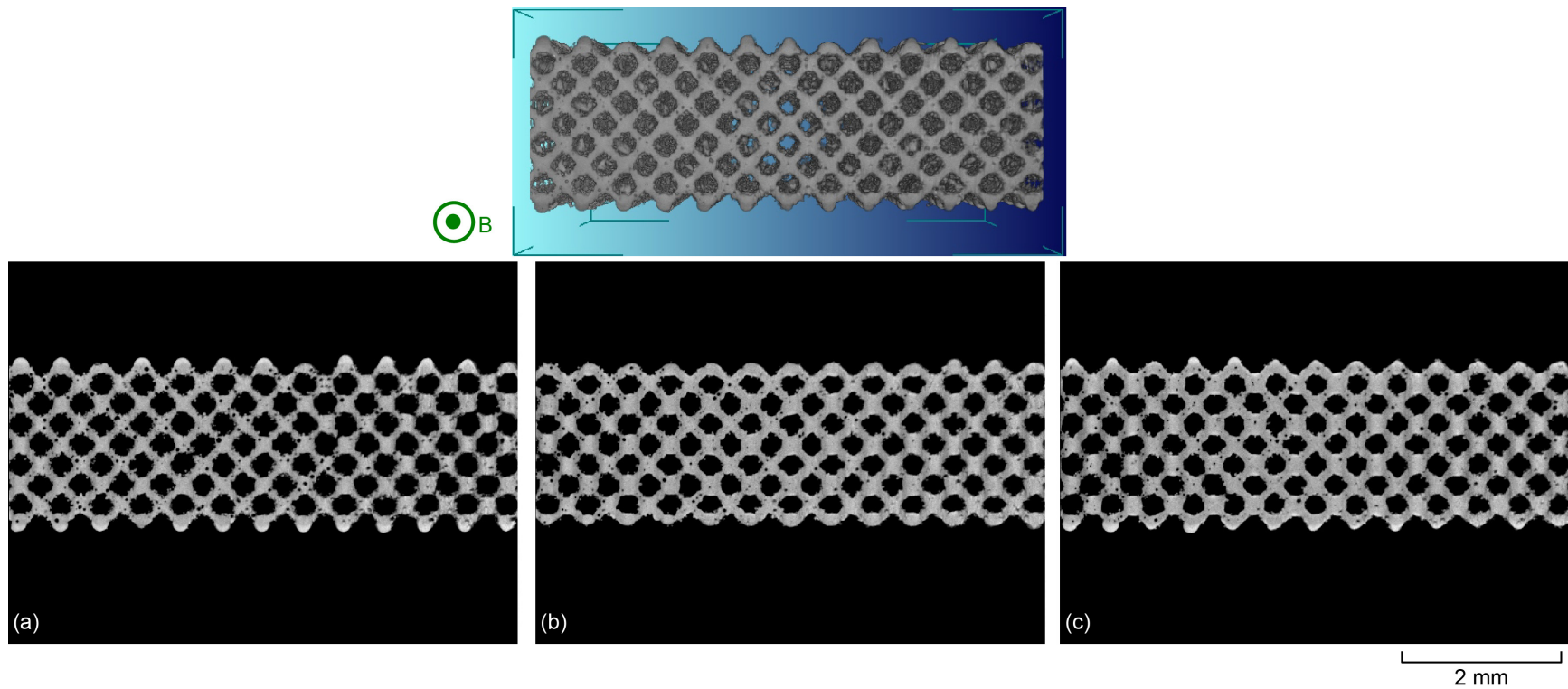


Figure 9.—The top view of lattice block 1a showing CT-derived volume and transverse sections. The building (B) direction is shown. (a) CT volume. (b) Corner nodes. (c) Intermediate struts. (d) Center nodes.

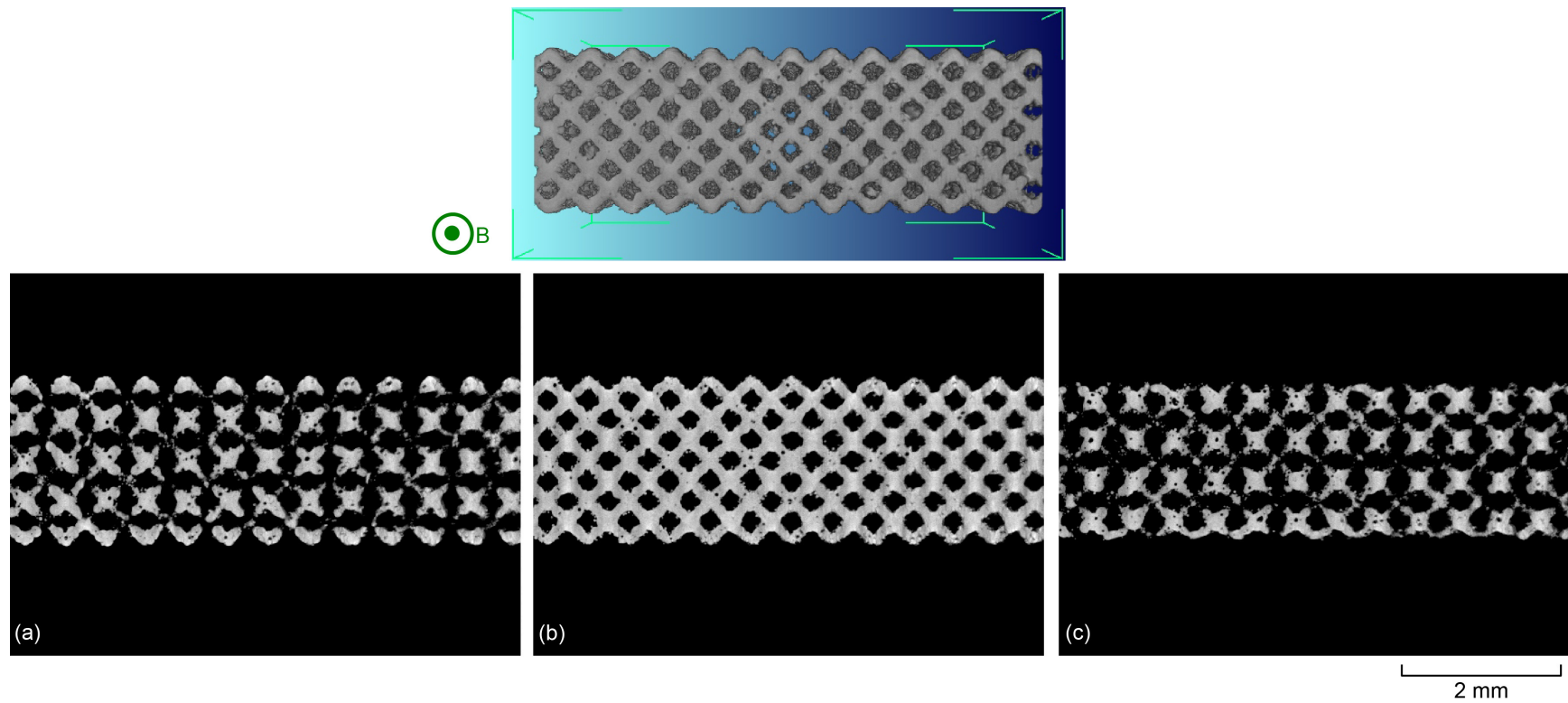


Figure 10.—The top view of lattice block IIa showing CT-derived volume and transverse sections. The building (B) direction is shown. (a) CT section. (b) Corner nodes. (c) Intermediate struts. (d) Center nodes.

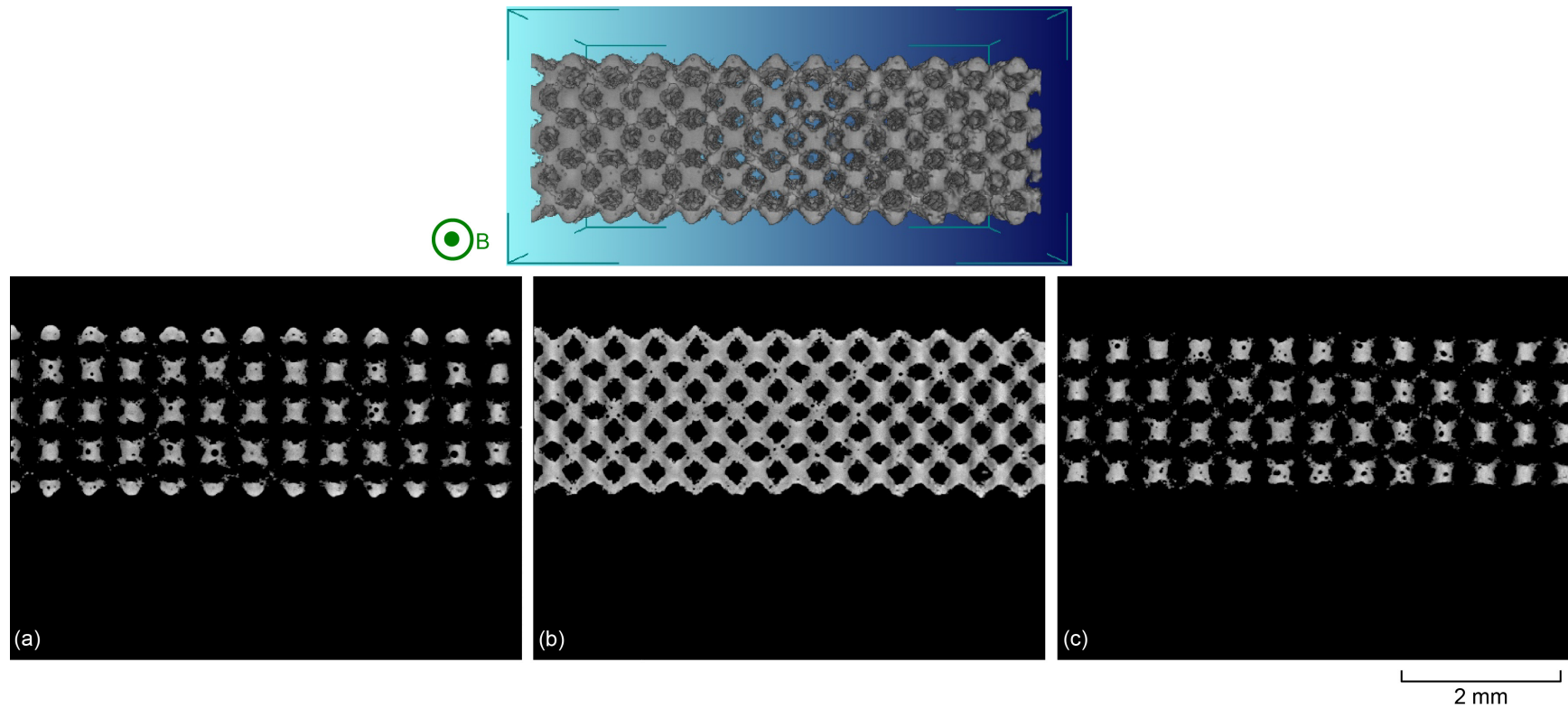


Figure 11.—The top view for lattice block IIIa showing CT-derived volume and transverse sections. The building (B) direction is shown. (a) CT volume. (b) Corner nodes, (c) Intermediate struts. (d) Center nodes.

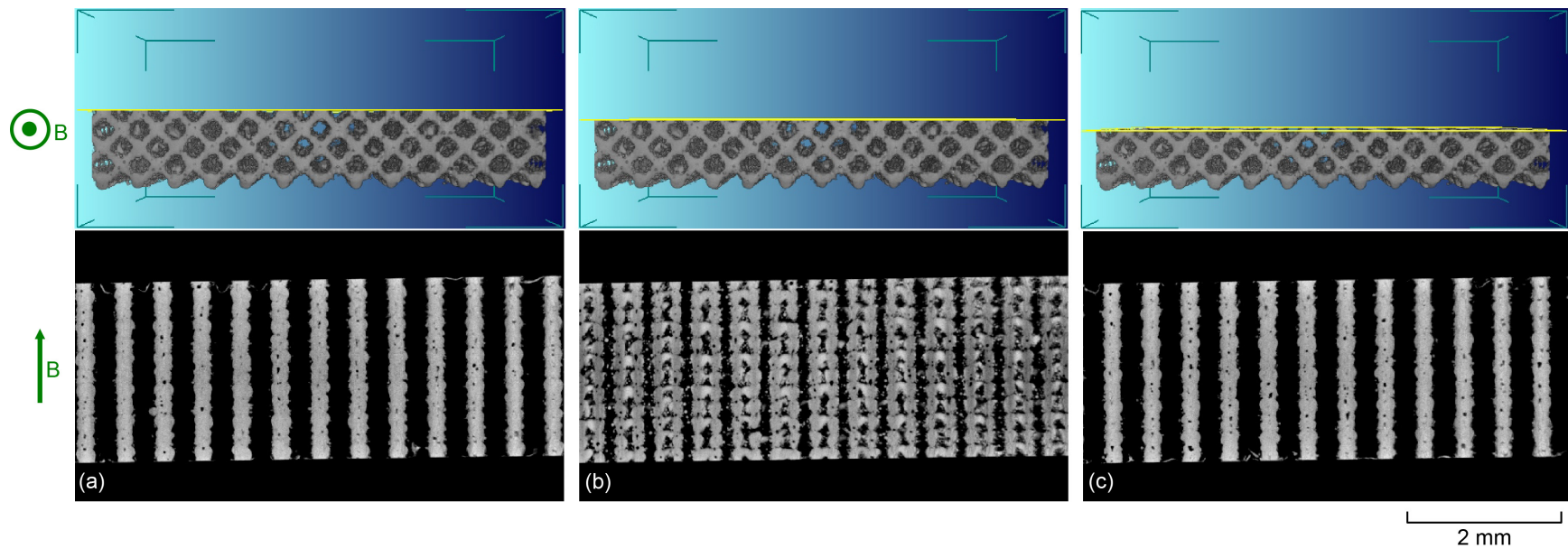


Figure 12.—The top view showing CT-derived volume for lattice block 1a, showing indicated longitudinal sections oriented parallel to the building (B) direction.
 (a) Corner nodes. (b) Intermediate struts. (c) Center nodes.

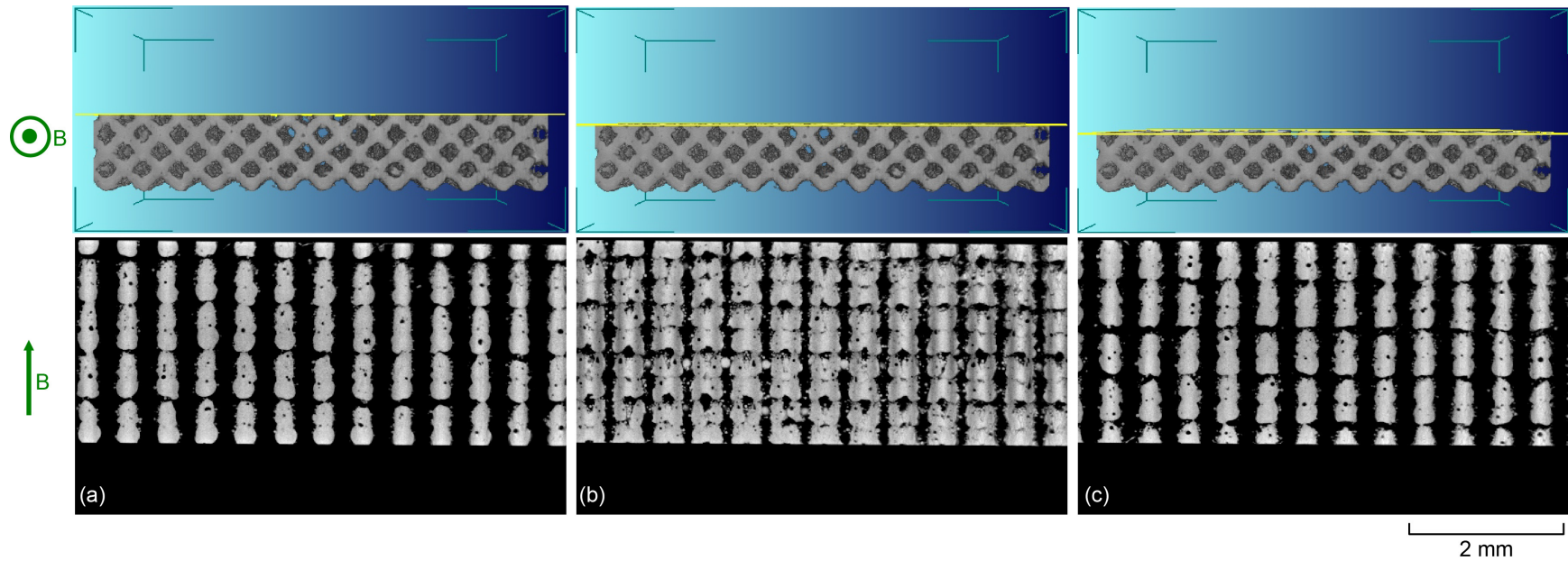


Figure 13.—The top view of CT-derived volume for lattice block IIa, showing longitudinal sections oriented parallel to the building (B) direction. (a) Corner nodes. (b) Intermediate struts. (c) Center nodes.

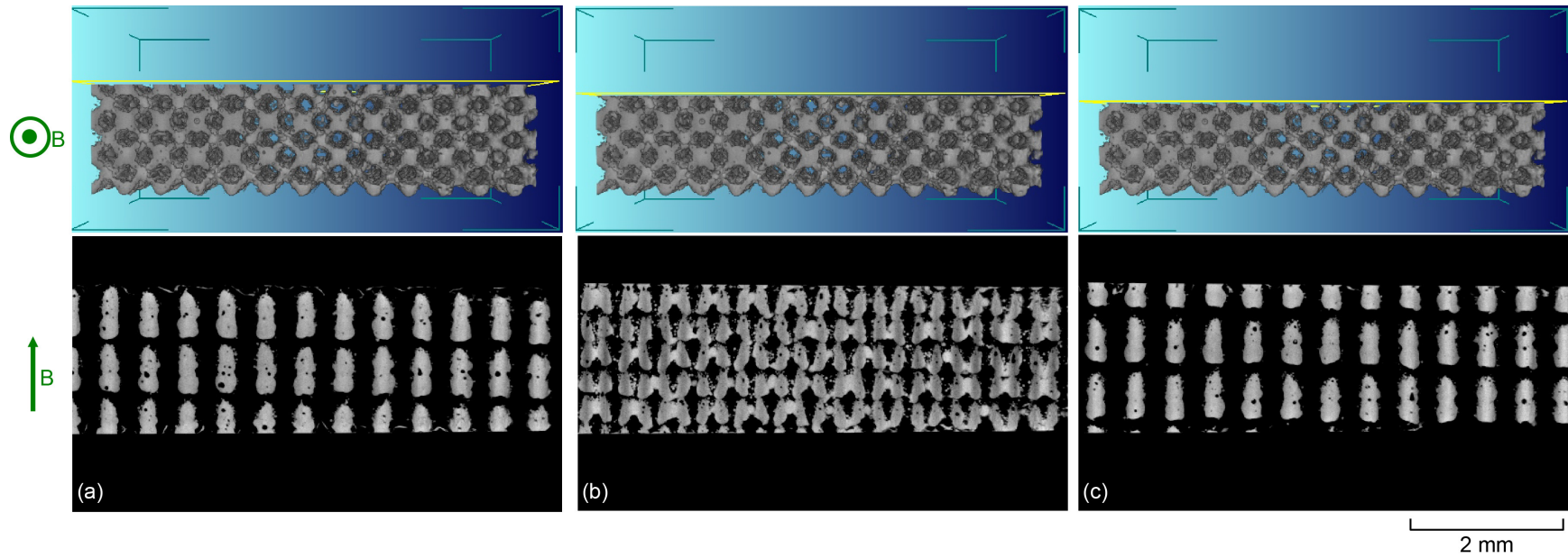


Figure 14.—The top view of CT-derived volume for lattice block IIIa, showing longitudinal sections oriented parallel to the building (B) direction. (a) Corner nodes. (b) Intermediate struts. (c) Center nodes.

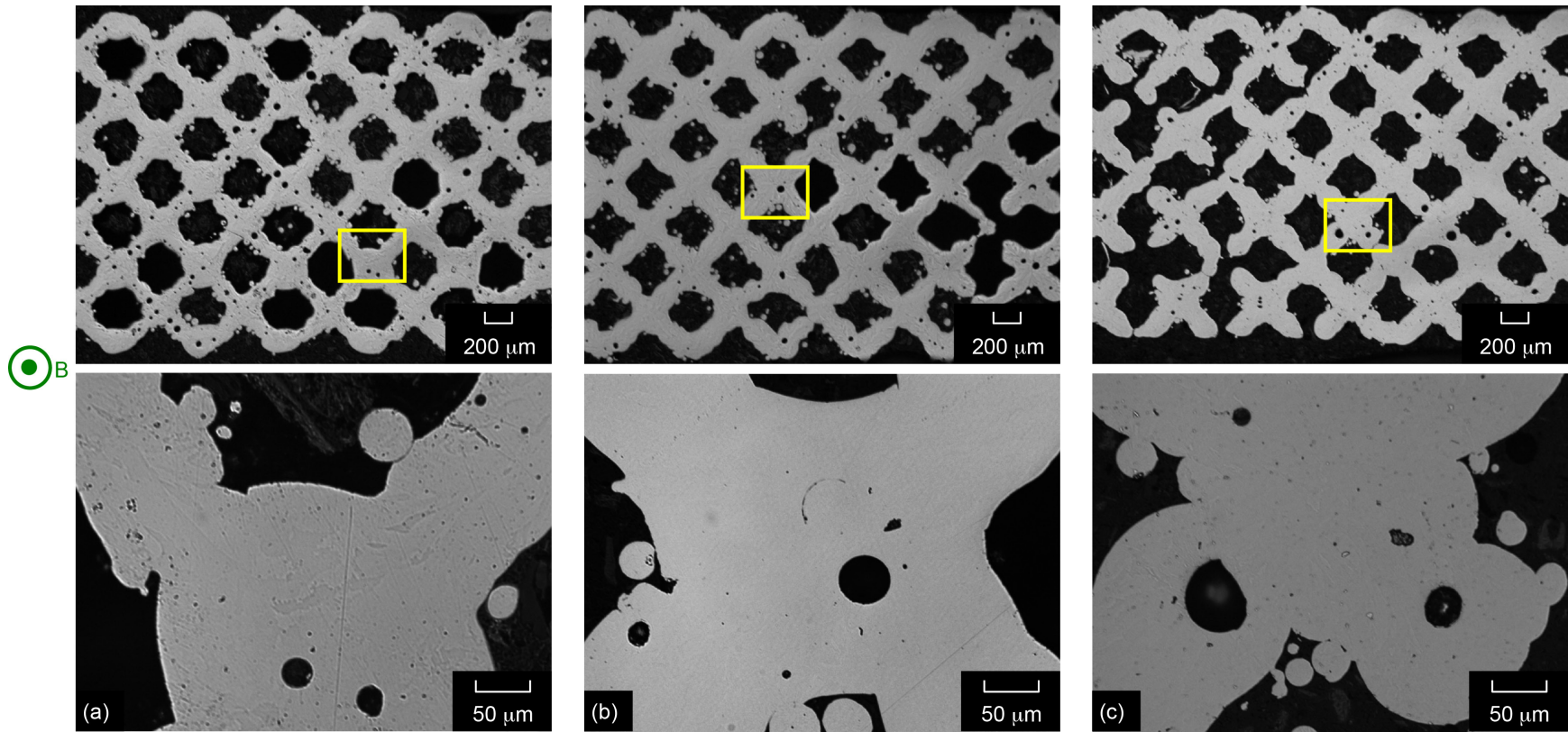


Figure 15.—Optical images of metallographic sections prepared transverse to the building (B) direction shown. (a) Ia. (b) IIa. (c) IIIa.

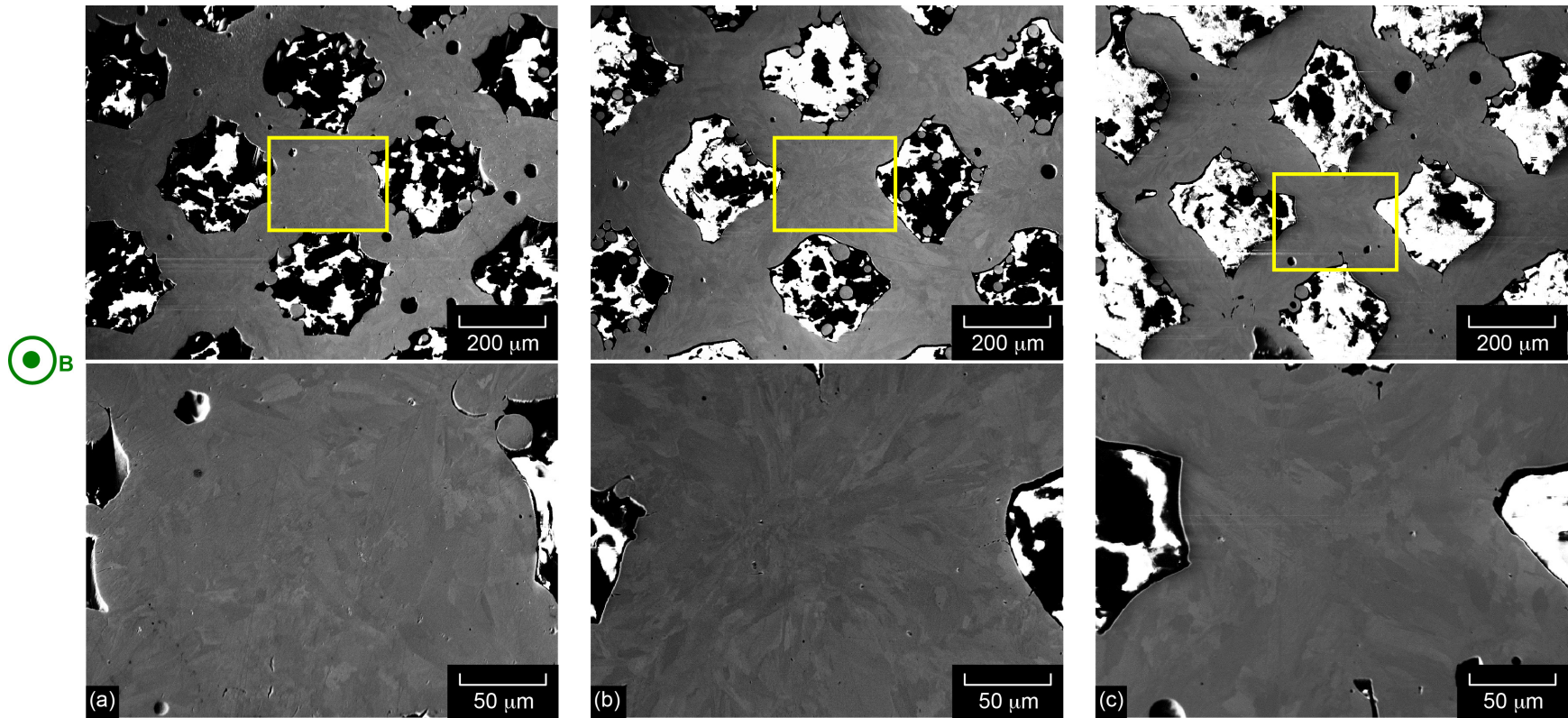


Figure 16.—SEM images of metallographic sections prepared transverse to the building (B) direction shown. (a) Ia. (b) IIa. (c) IIIa.

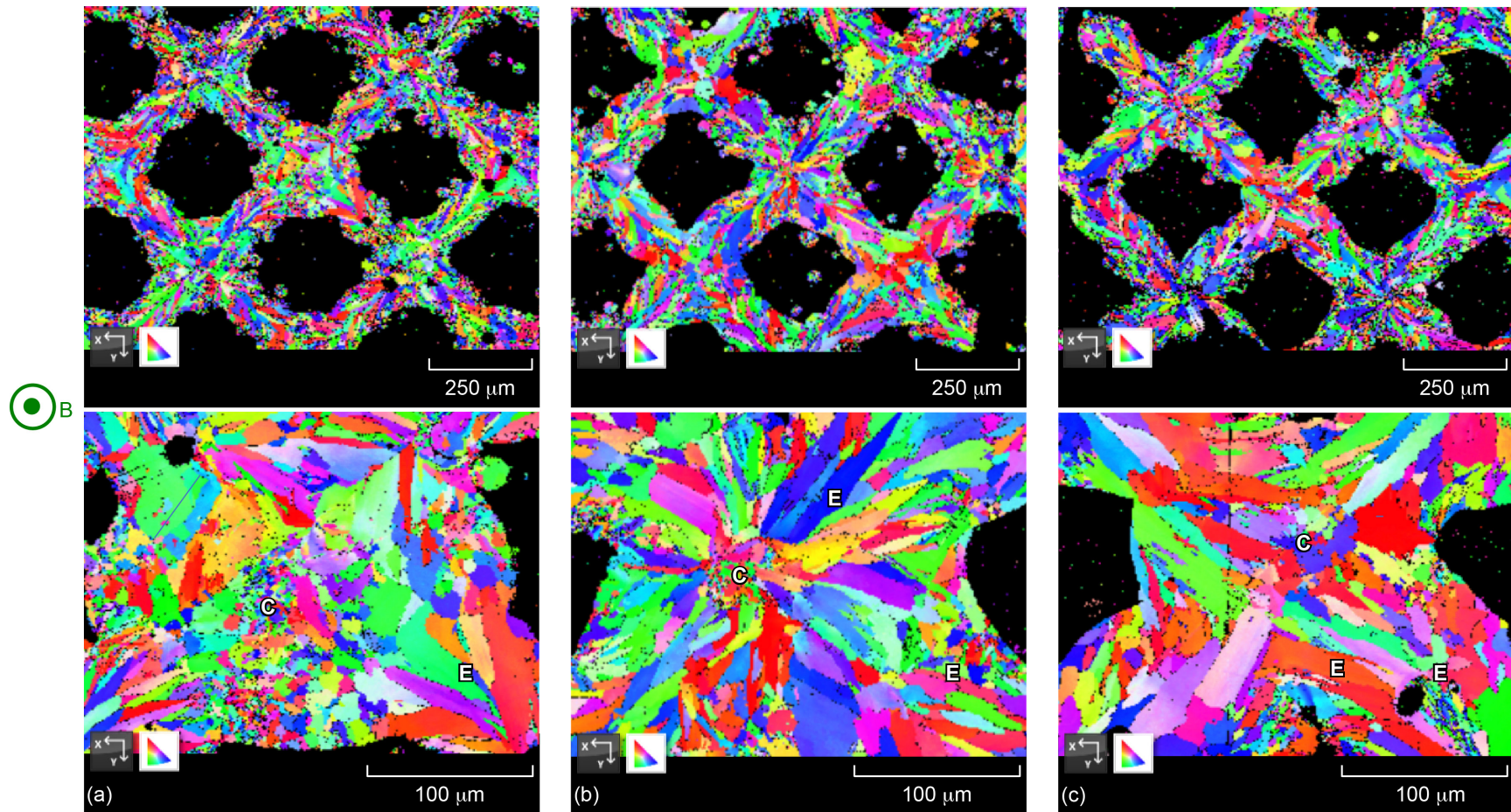


Figure 17.—EBSD of transverse metallographic sections in Figure 16, showing some grains elongated (E) along struts and other smaller grain colonies (C). The building (B) direction is shown. (a) Ia. (b) IIa. (c) IIIa.

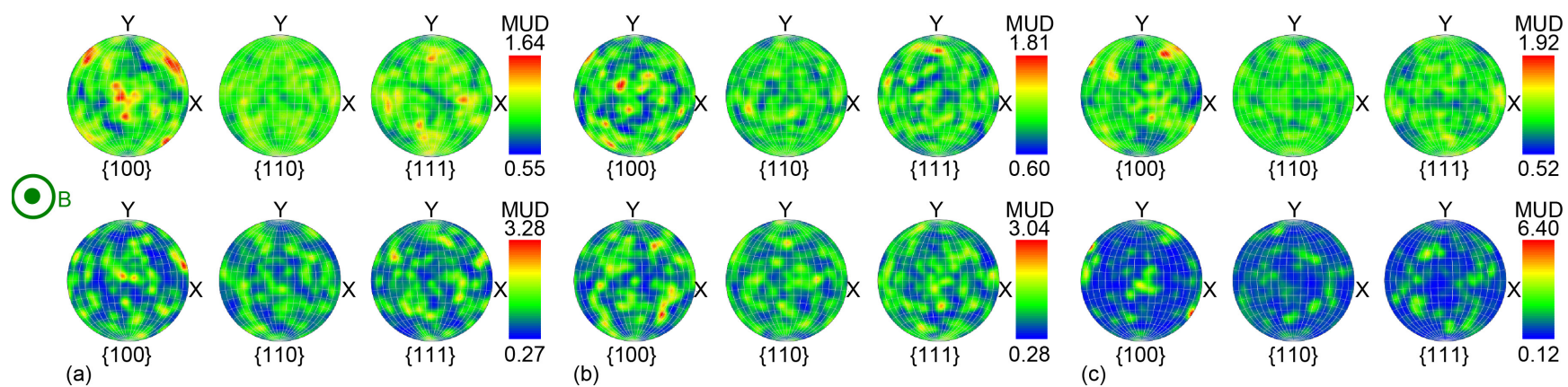


Figure 18.—Corresponding inverse pole figures from EBSD-analyzed areas depicted in Figure 16 and Figure 17. The building (B) direction is shown. (a) Ia. (b) IIa. (c) IIIa.

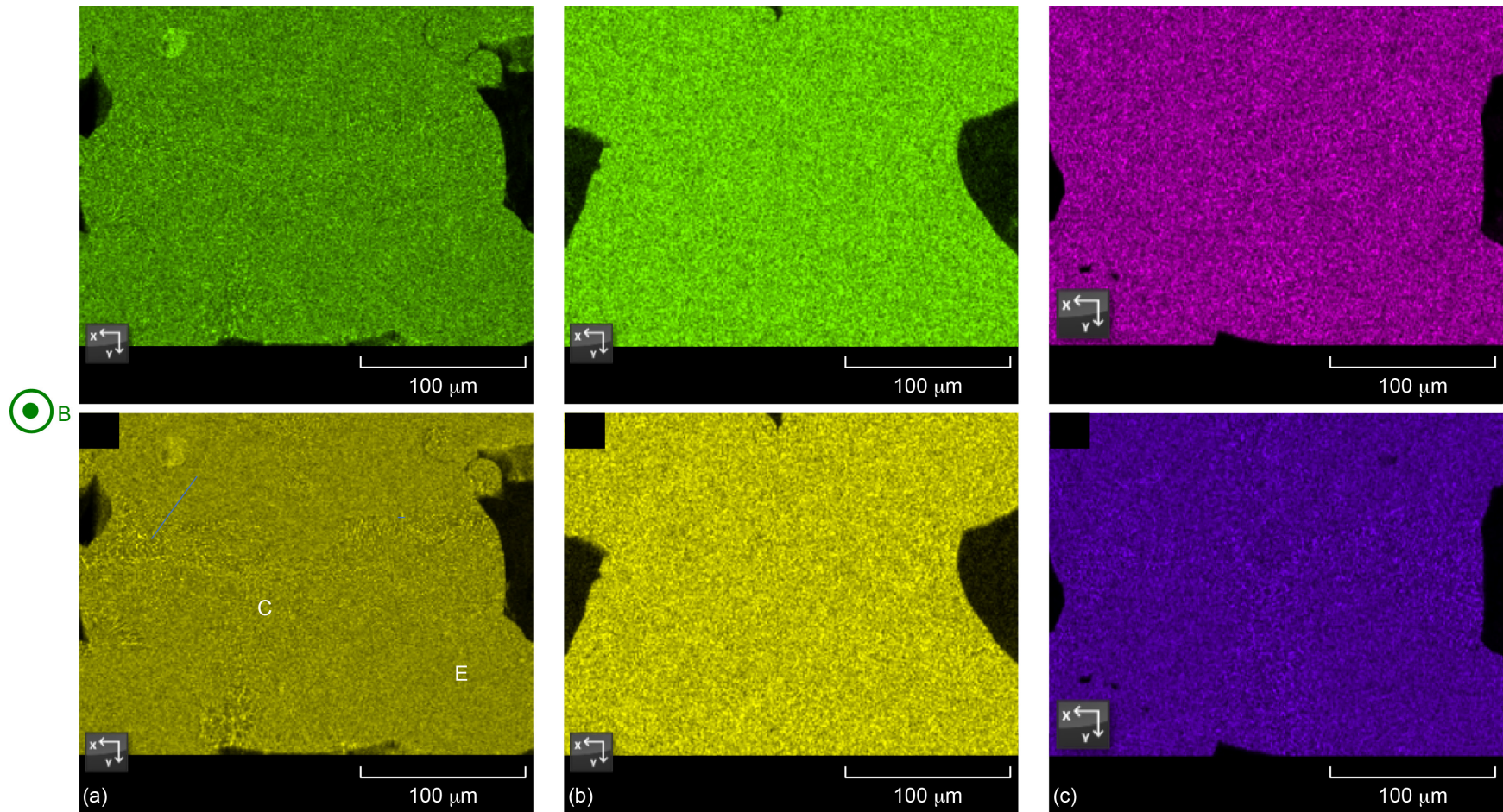


Figure 19.—EDS of transverse metallographic sections, showing only minor segregation of Mo and Nb across this plane. The building (B) direction is shown.
 (a) Ia. (b) IIa. (c) IIIa.

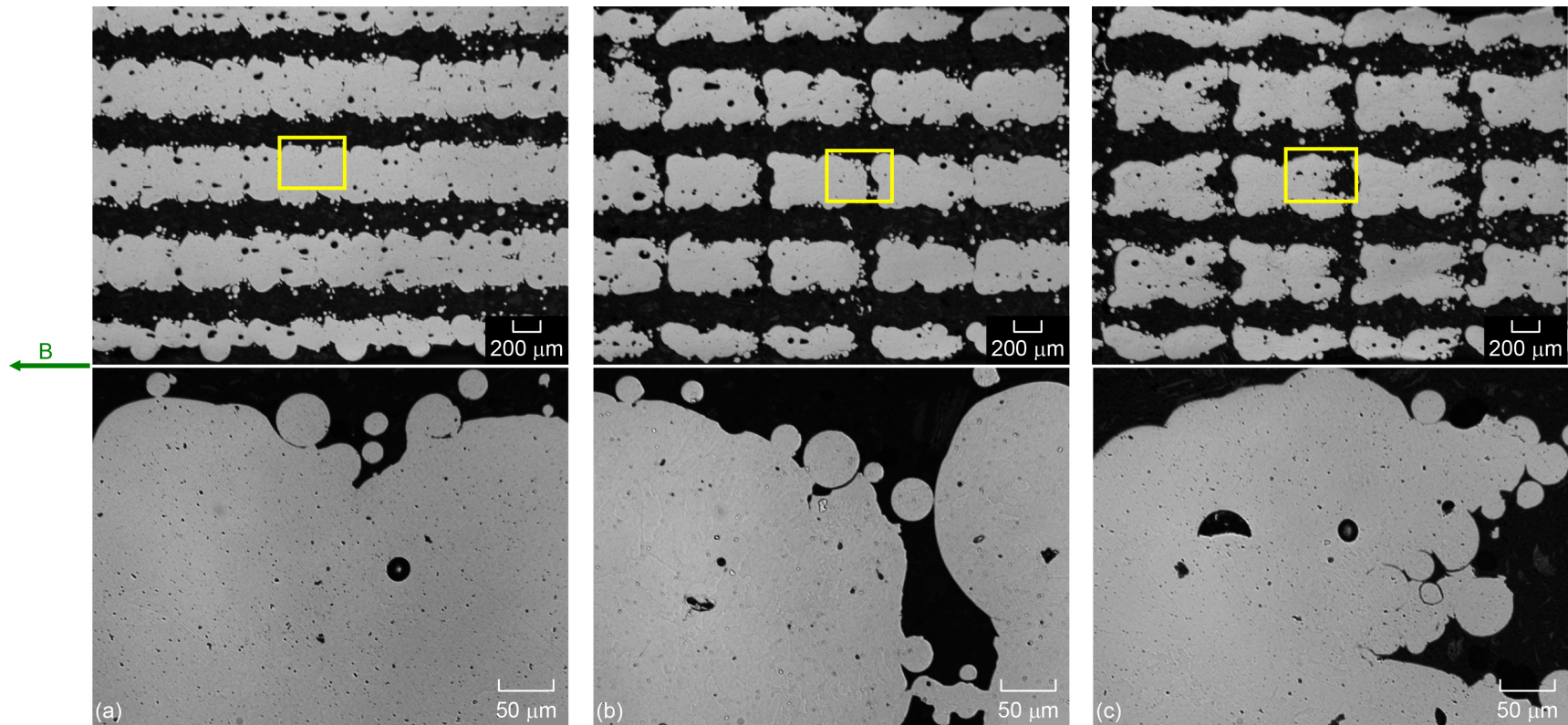


Figure 20.—Optical images of longitudinal thickness metallographic sections intersecting corner nodes. The building (B) direction is horizontal. (a) Ia. (b) IIa. (c) IIIa.

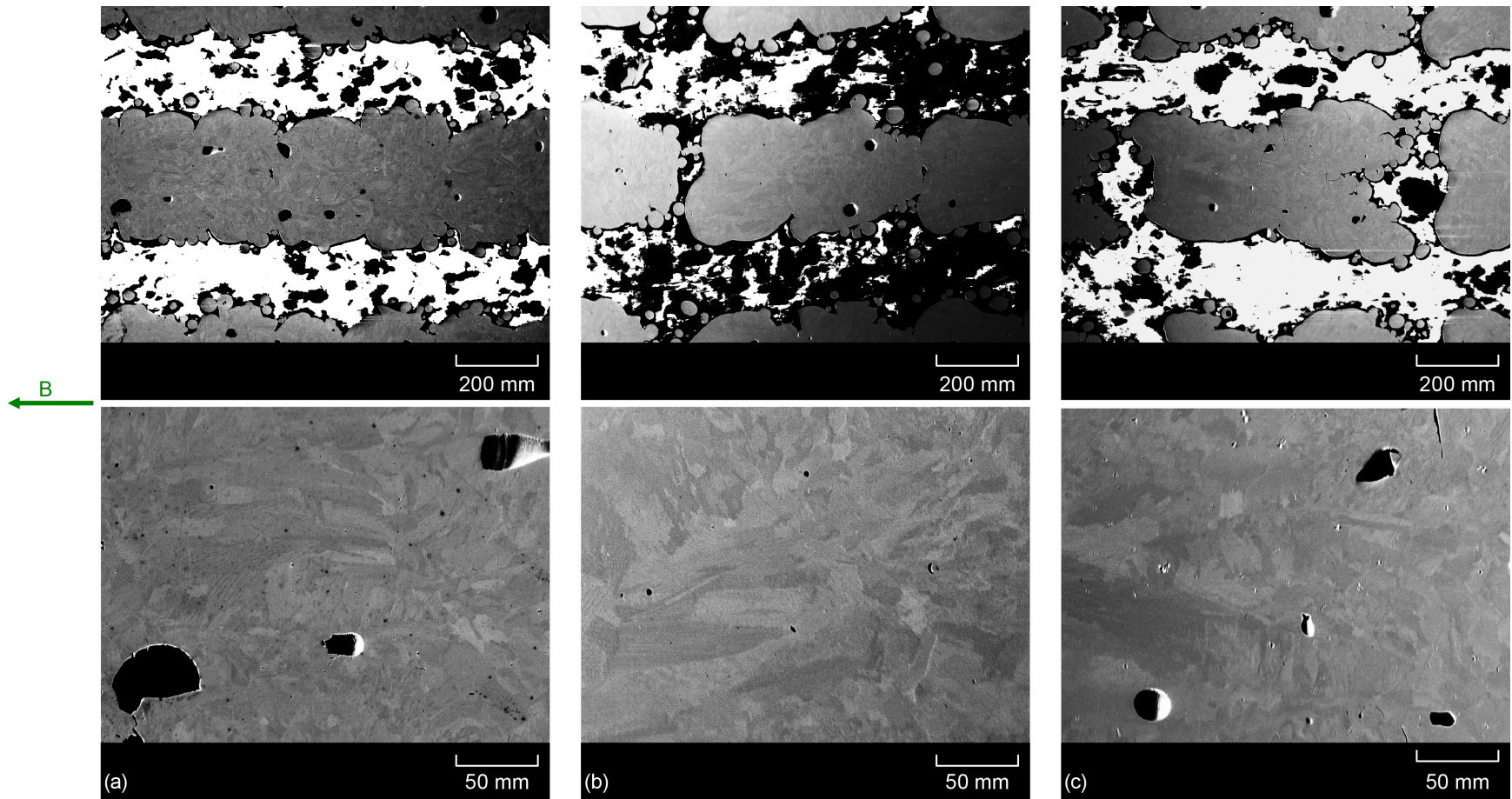


Figure 21.—SEM Images of longitudinal-thickness metallographic sections. The building (B) direction is horizontal. (a) Ia. (b) IIa. (c) IIIa.

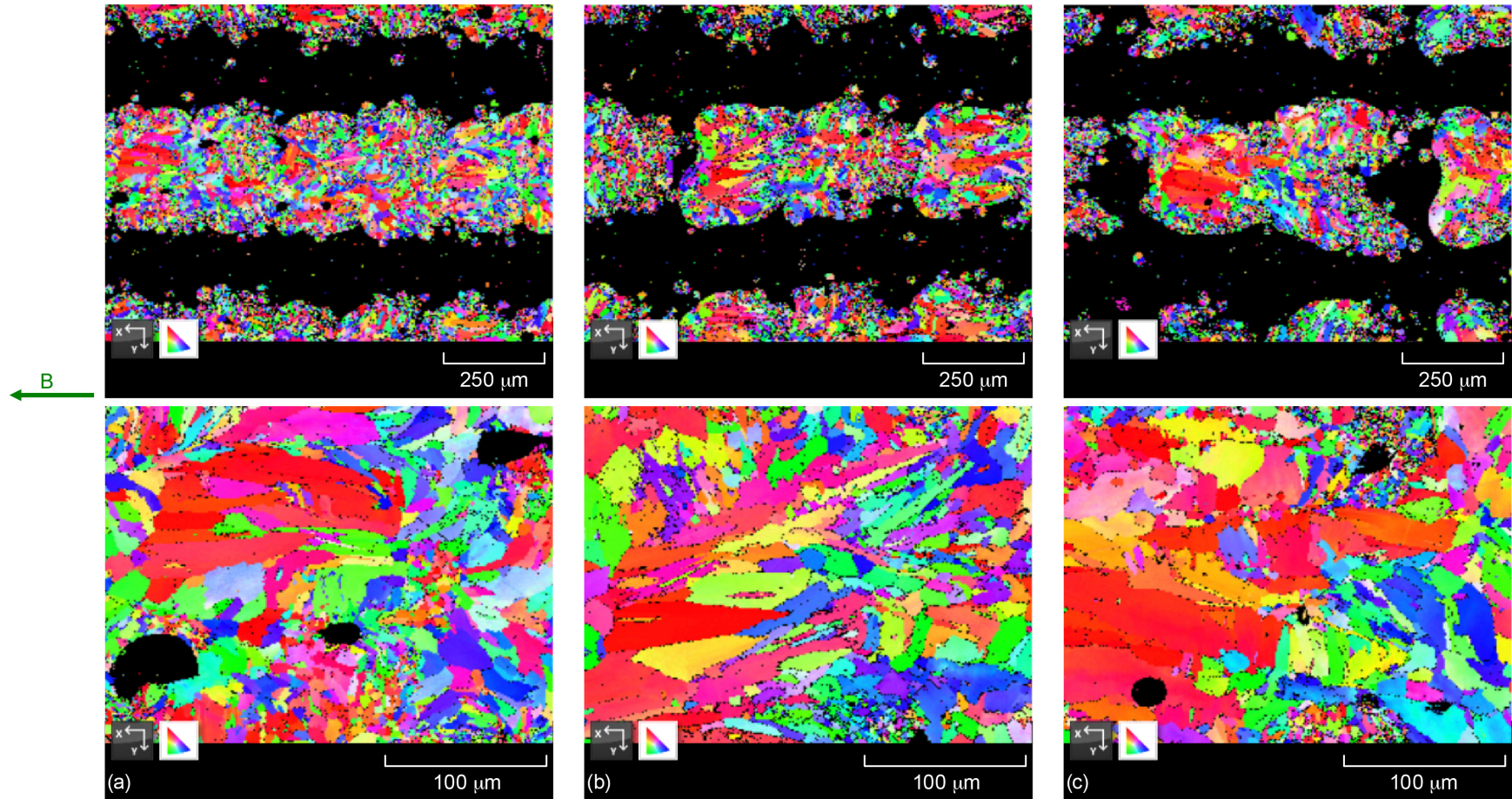


Figure 22.—EBSD images of longitudinal-thickness metallographic sections in Figure 21, showing grains less often elongated in the horizontal building (B) direction of this plane. (a) Ia. (b) IIa. (c) IIIa.

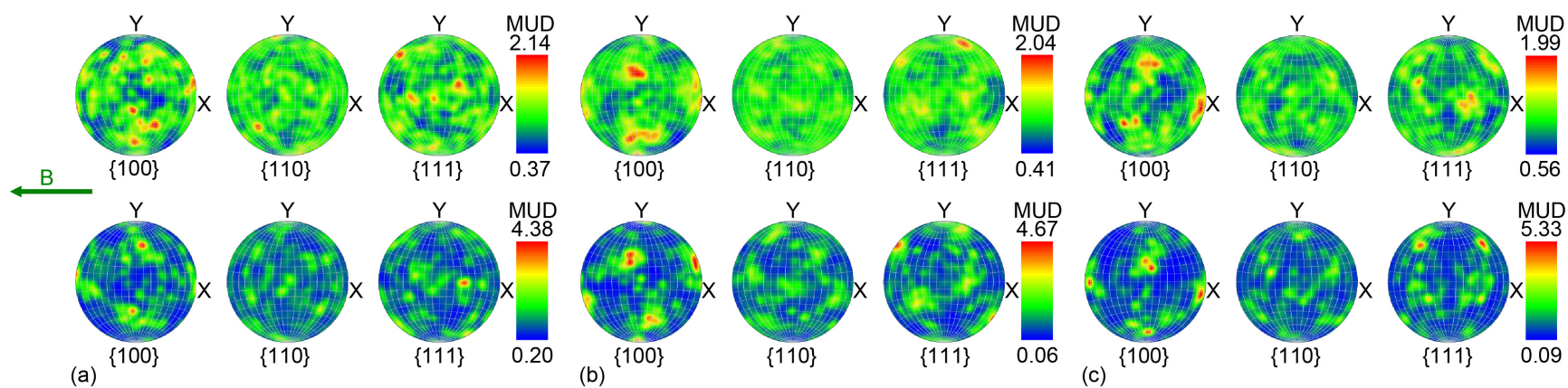


Figure 23.—Corresponding inverse pole figures from EBSD-analyzed areas depicted in Figure 21 and Figure 22. The building (B) direction is shown. (a) Ia. (b) IIa. (c) IIIa.

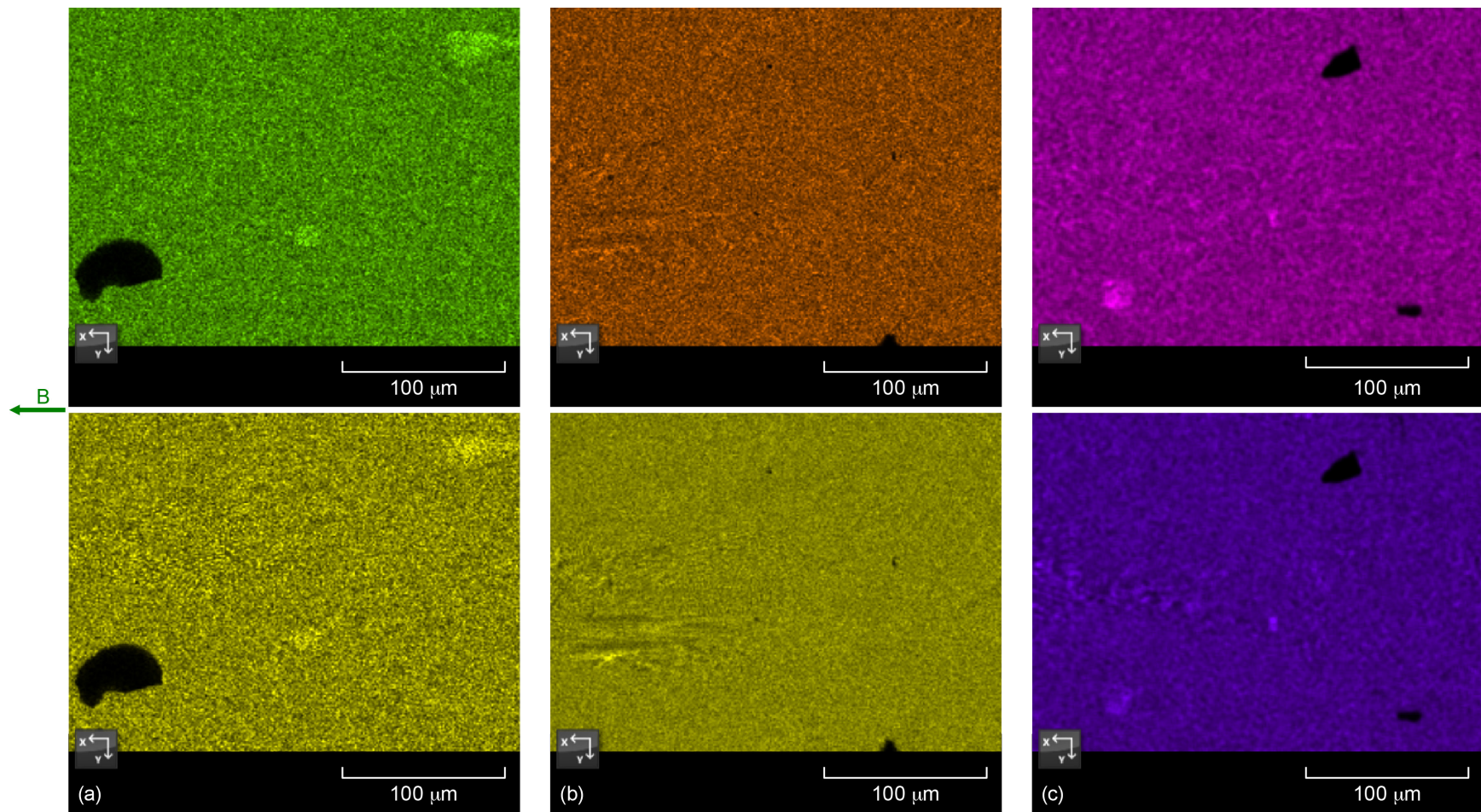


Figure 24.—EDS maps of longitudinal-thickness metallographic sections of Figure 19 and Figure 20, showing only minor segregation of Mo and Nb across this plane. The building (B) direction is shown. (a) Ia. (b) IIa. (c) IIIa.

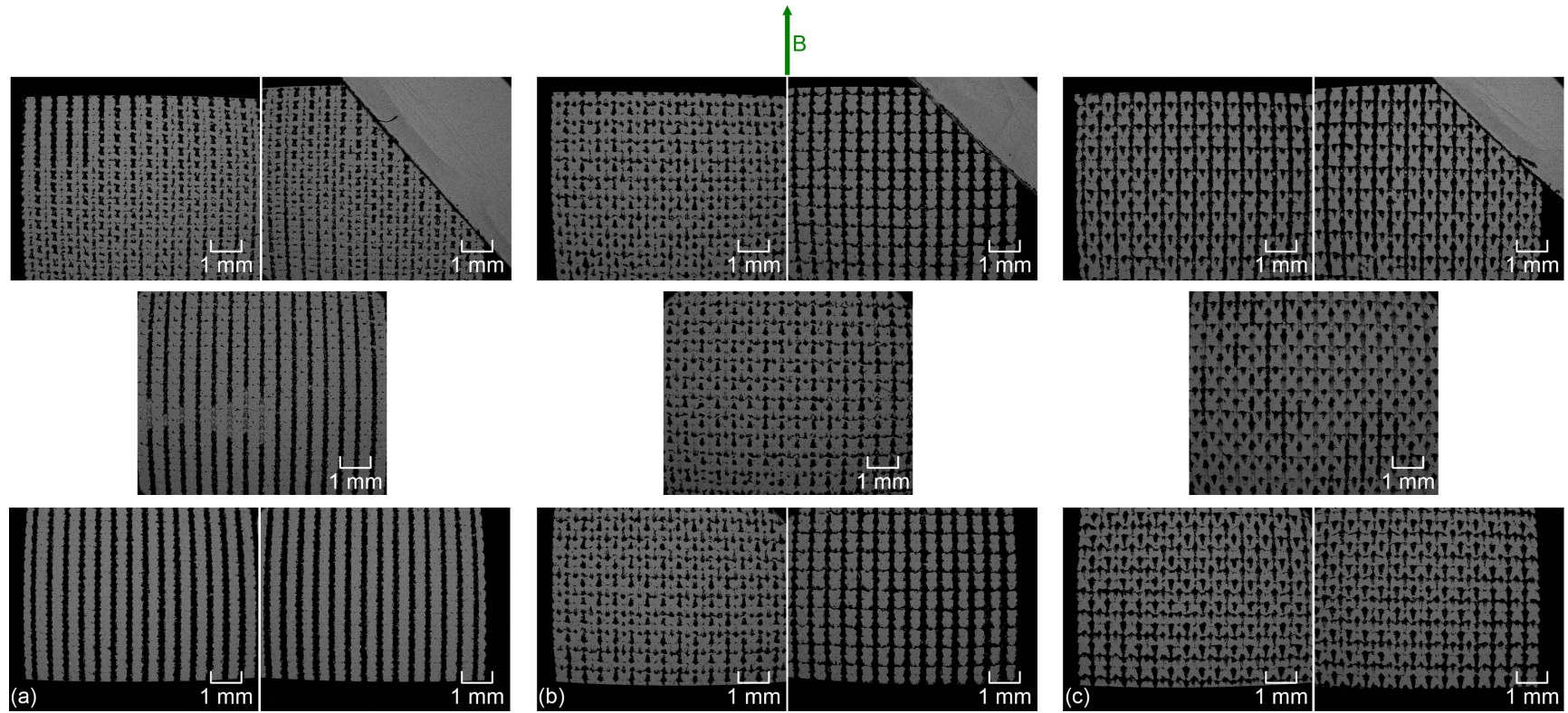


Figure 25.—Optical images of large-area longitudinal-width metallographic sections prepared for x-ray evaluation of overall texture. The building (B) direction is shown. Copper tape is attached in the upper right corner for grounding. (a) Ia. (b) IIa. (c) IIIa.

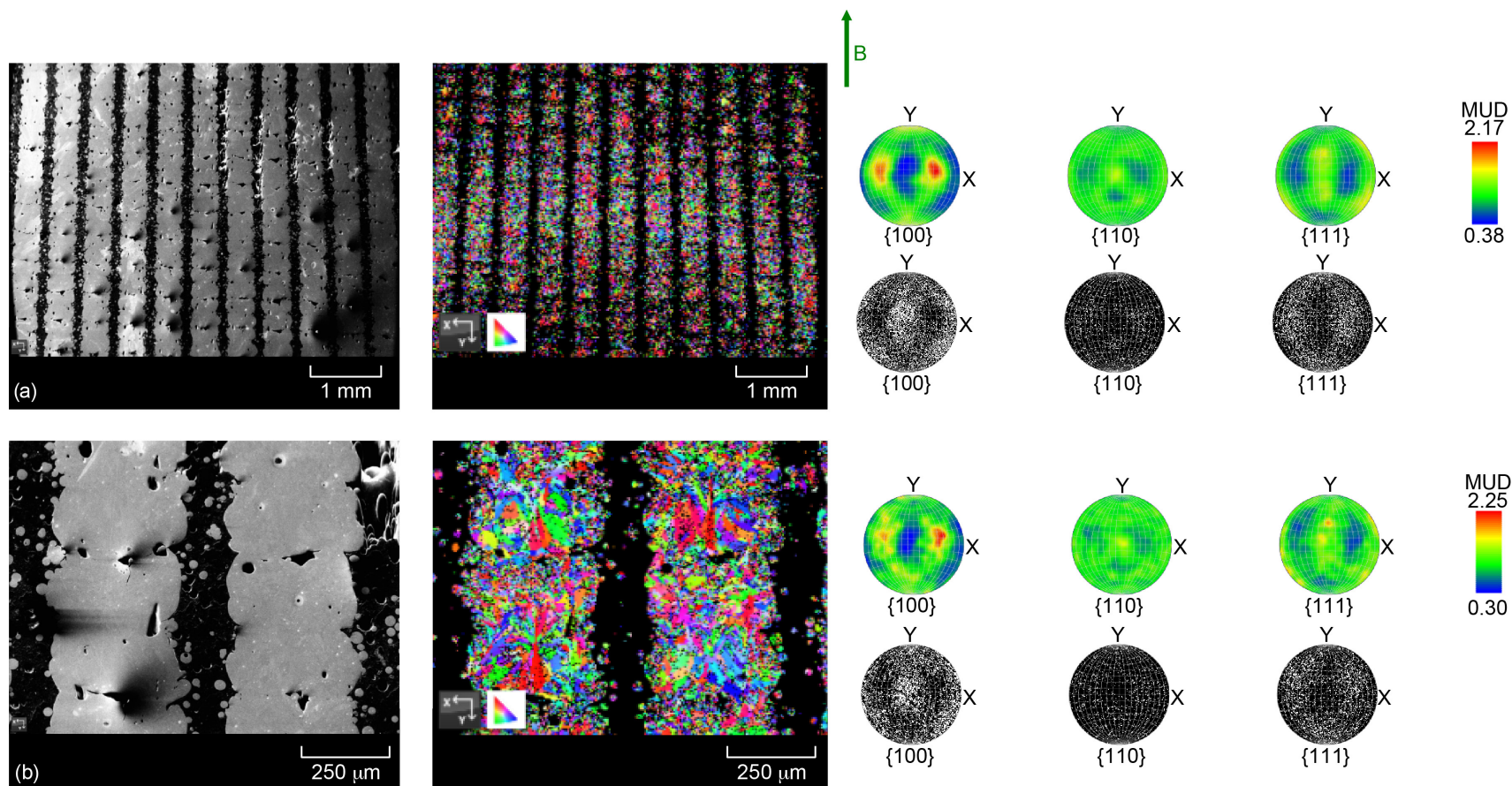


Figure 26.—Typical SEM images, EBSD images, and pole figures of the large-area longitudinal-width metallographic section prepared for x-ray evaluation of overall texture for Ia, acquired from the center. The building (B) direction is shown. (a) Lowest (50×) magnification. (b) Intermediate (250×) magnification.

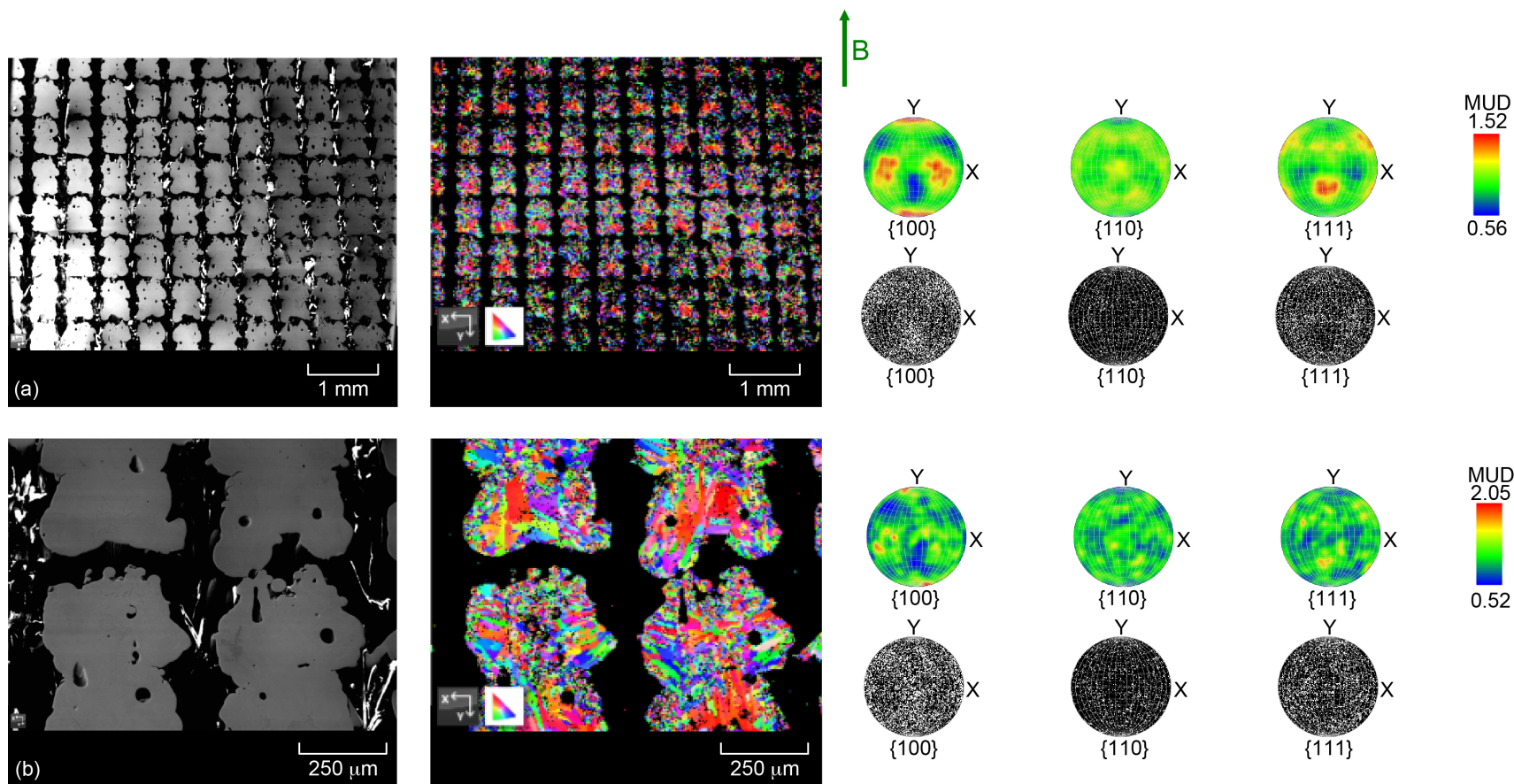


Figure 27.—Typical SEM images, EBSD images, and pole figures of the large area longitudinal-width metallographic section prepared for x-ray evaluation of overall texture for IIa, acquired from the center. The building (B) direction is shown. (a) Lowest (50 $\times$) magnification. (b) Intermediate (250 $\times$) magnification.

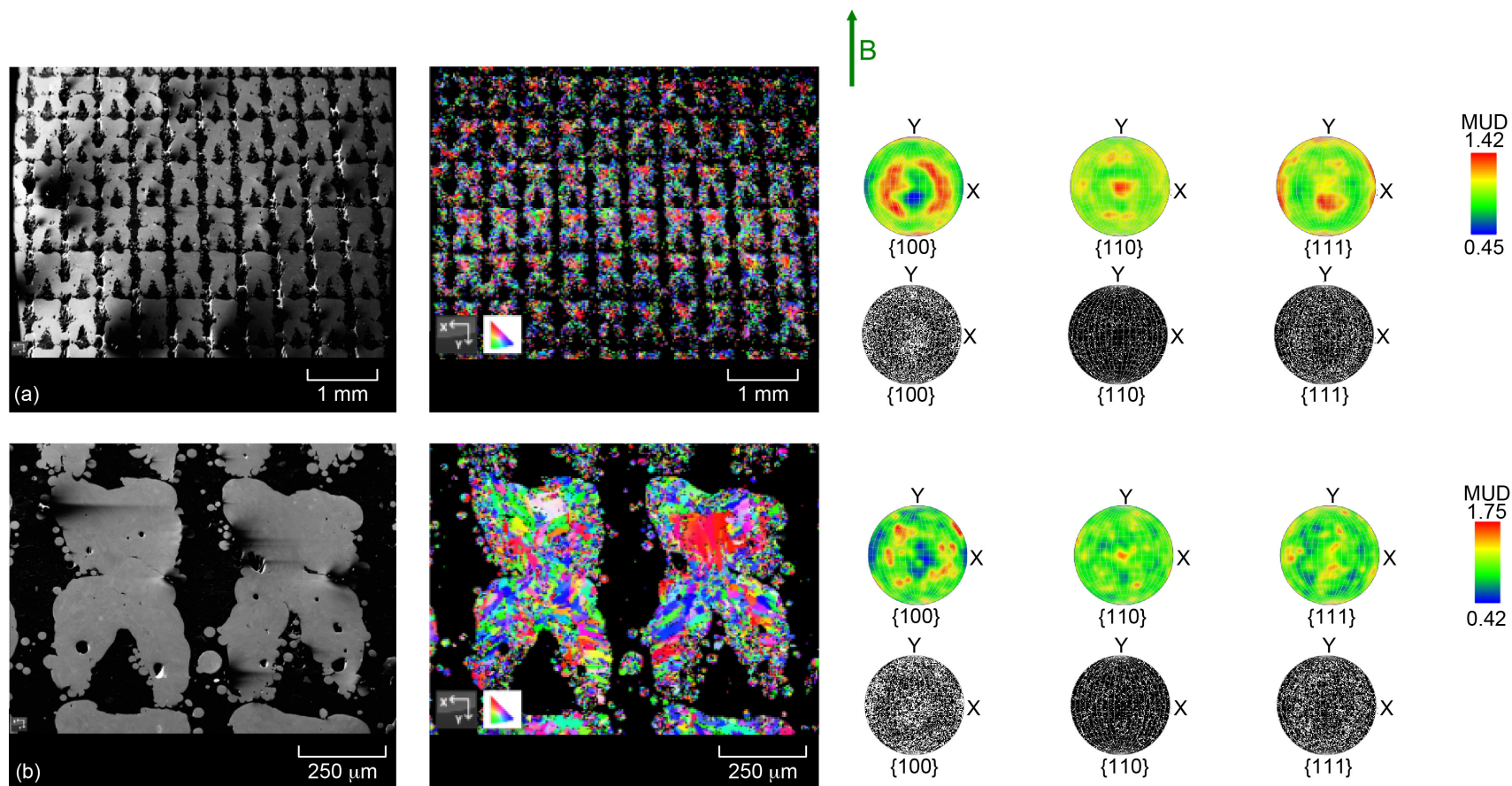


Figure 28.—Typical SEM images, EBSD images, and pole figures of the large area longitudinal-width metallographic section prepared for x-ray evaluation of overall texture for IIIa, acquired from the center. The building (B) direction is shown. (a) Lowest (50 $\times$) magnification. (b) Intermediate (250 $\times$) magnification.

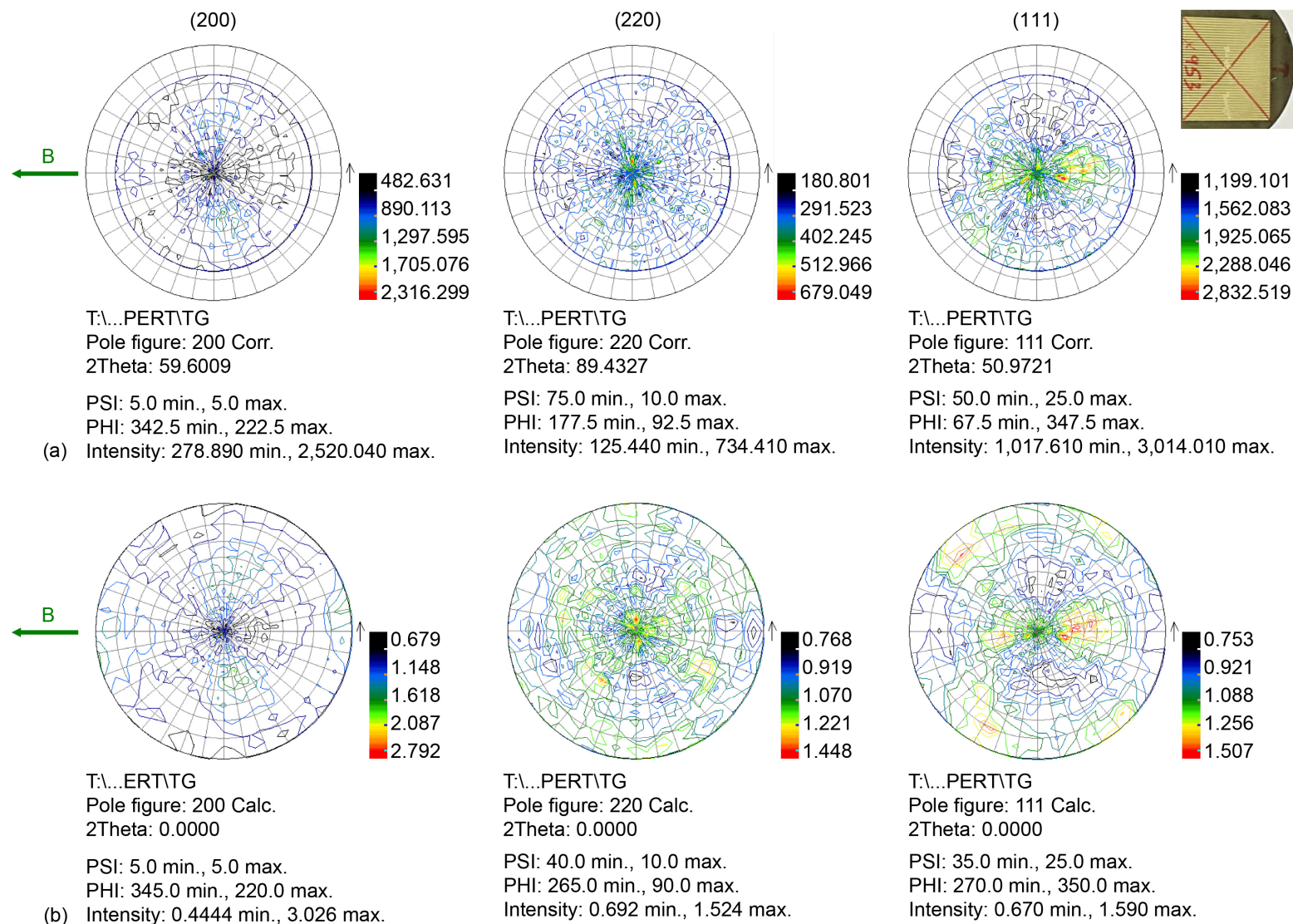


Figure 29.—X-ray analysis of crystallographic texture for the (200), (220), and (111) poles of large longitudinal-width metallographic section Ia. The building (B) direction is shown. (a) Experimental. (b) Calculated.

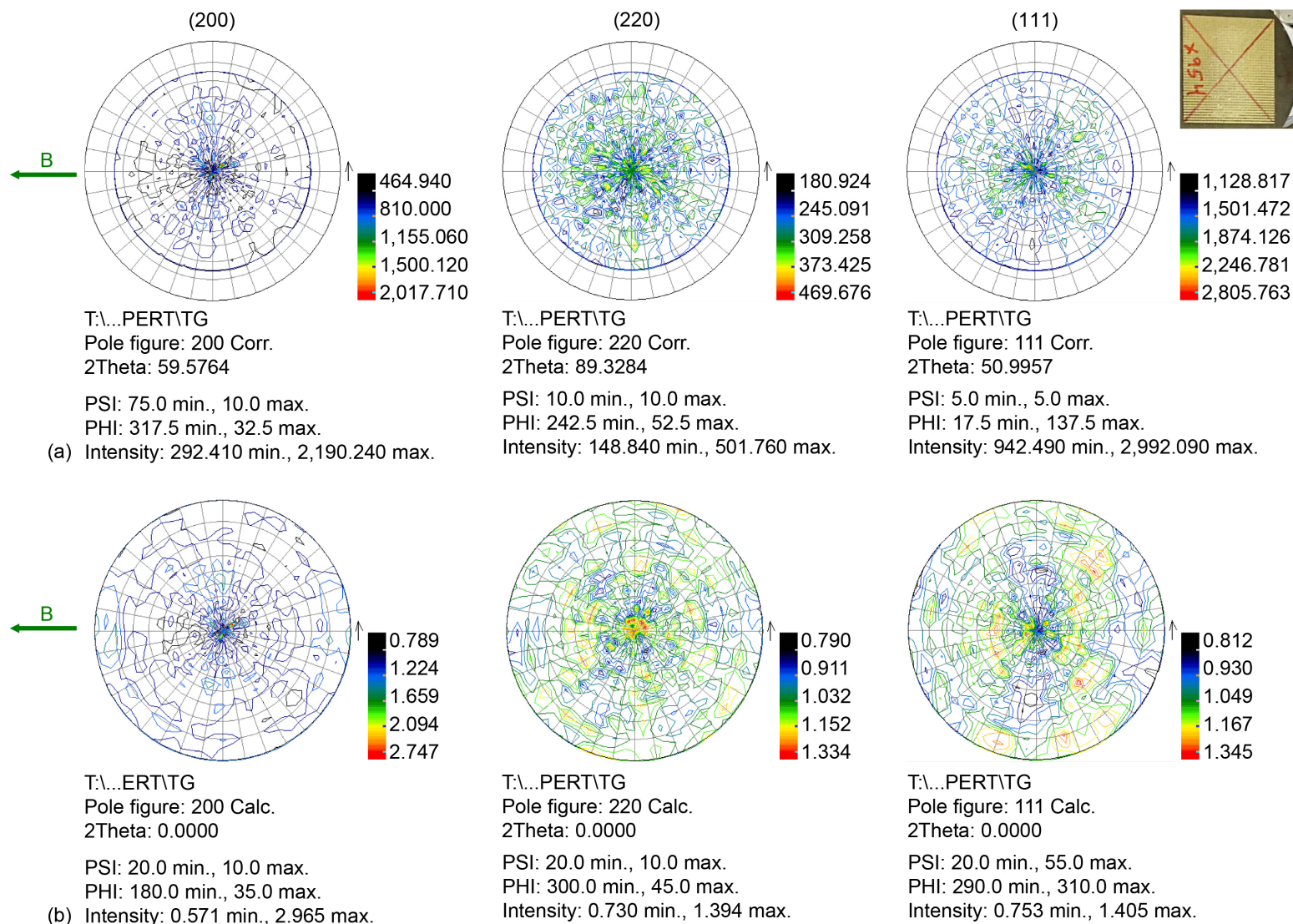


Figure 30.—Crystallographic texture measured by x-ray diffraction of large longitudinal-width metallographic section for IIa. The building (B) direction is shown. (a) Experimental. (b) Calculated.

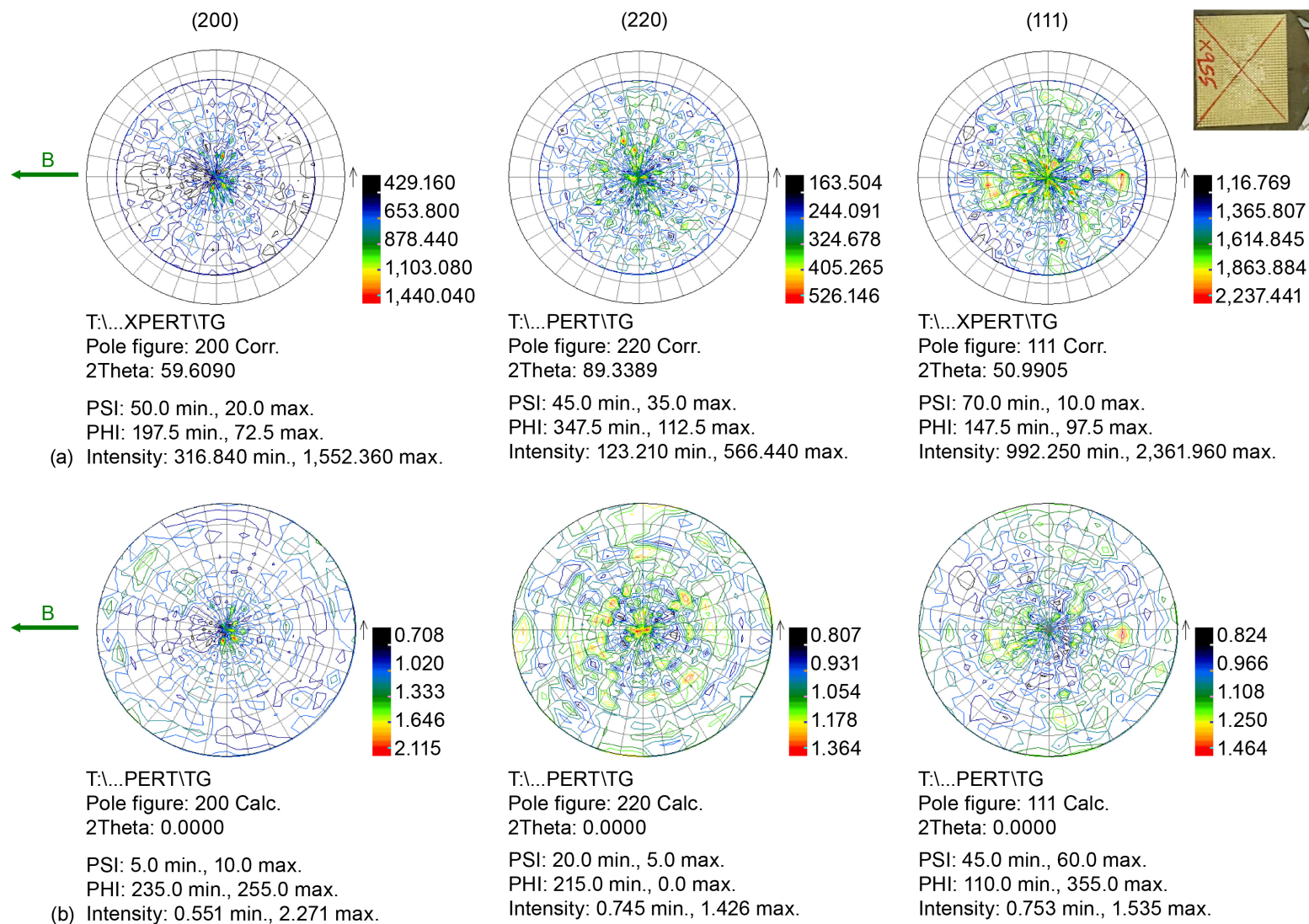


Figure 31.—Crystallographic texture measured by x-ray diffraction of large longitudinal-width metallographic section for IIIa. The building (B) direction is shown. (a) Experimental. (b) Calculated.

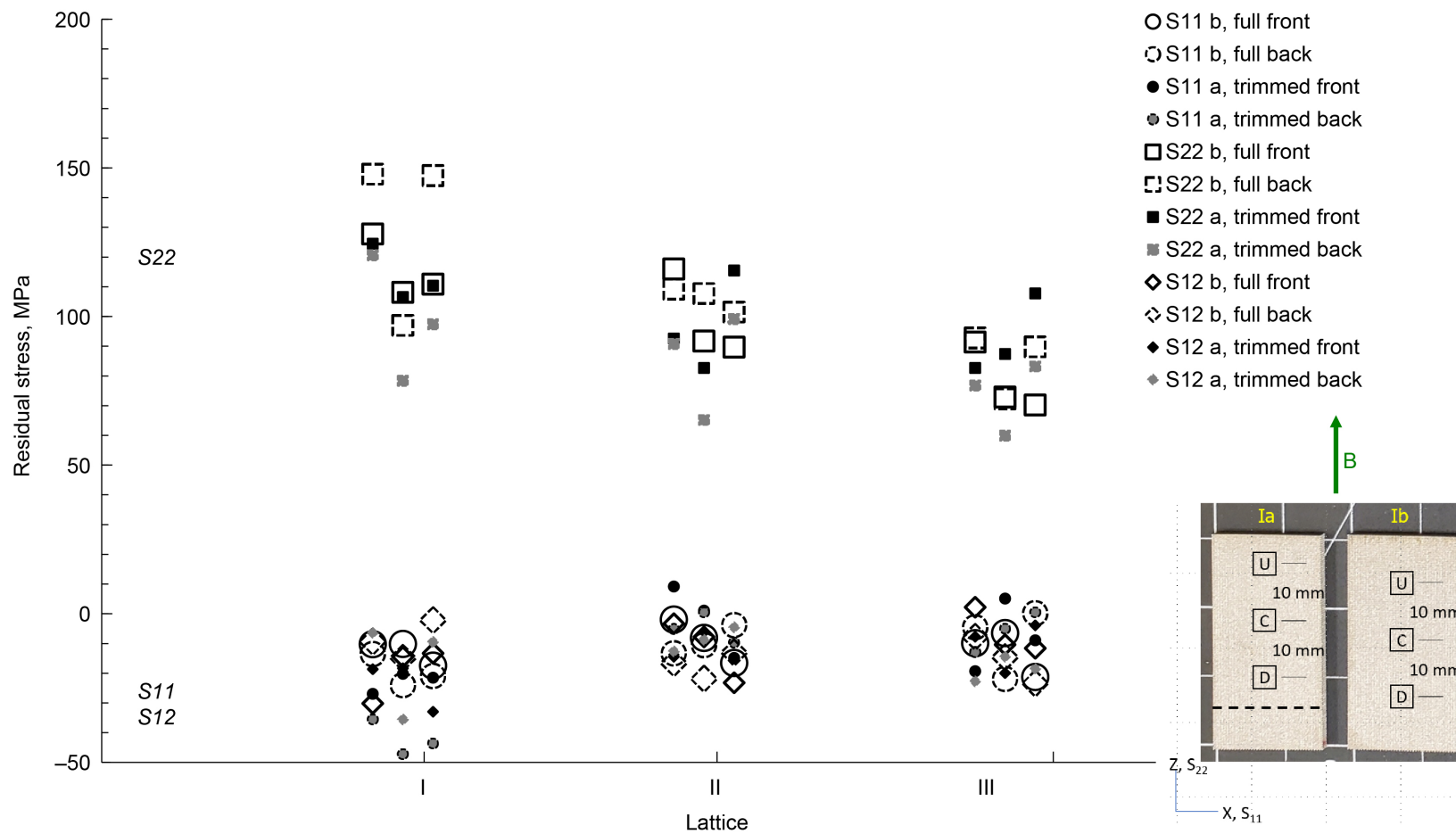


Figure 32.—Residual normal stresses S11 (circles), S22 (squares), and shear stress S12 (diamonds) averaged across consistently spaced 4-mm by 4-mm square locations shown in Figure 3 on both the front and back faces on blocks a and b of each lattice I, II, and III. Typical locations and associated coordinate directions are shown at right. The building (B) direction is shown.

