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主　論　文　の　要　旨

論文題目　**Enhancement in compressive properties of additive-manufactured metallic lattice structures through experimental and numerical approaches**
(実験及び数値解析による積層造形ラティス構造体の圧縮特性の向上)

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論　文　内　容　の　要　旨

In the present study, the compressive properties of additive-manufactured metallic lattice structures were investigated and enhanced through experimental and numerical approaches for the potentials utilized in a broad array of applications. Laser powder bed fusion process using aluminum alloy powder were applied to manufacture metallic lattice structures. First, the lattice structures consisting of three different unit cell types were studied to elucidate the effect of geometrical features on the deformation behaviors and their associated compressive properties. The shear band formation often occurring in lattice structures was then focused on. The mechanism, evolution process and preferential formation plane and direction of shear band were explored. An approach by adjusting strut diameter ratios to suppress the shear band formation was proposed and demonstrated. The improvement on the compressive performance of lattice structures was further attempted using novel design strategies. The mechanical responses and deformation behaviors of new lattice structures designed by mimicking topologically close-packed structure of C15 Laves phase were investigated. Finally, the hybrid lattice structures were proposed by combining bending-dominated and stretch-dominated unit cells. The effect of four spatial arrangement patterns of the two kinds of unit cells on the compressive behaviors of hybrid lattice structures were studied.

In Chapter 1, the significance of enhancement in the compressive properties of lattice structures for practical application were stated. The categorizations, designs, fabrication processes, and mechanical properties of lattice structures were detailed. The reported literatures were reviewed for a better understanding of state-of-art researches and current issues of lattice structures. The influence of unit cell type on the mechanical performance of lattice structures utilized as shock absorbers to dissipate impact energy has been not sufficiently investigated. The common phenomenon of shear band formation in lattice structures under compression prompts an unstable stress–strain curve, resulting in a significant reduction in the energy absorption capacity. The development and formation of shear band need to be clarified, and versatile approaches to suppress the shear band are required. Furthermore, creative lattice designs for more possibilities of superior properties should be explored. Accordingly, main objectives have been specified to address these issues and achieve the enhancement of mechanical properties of lattice structures.

In Chapter 2, the effect of different unit cell morphology including body-centered cubic (BCC), truncated octahedron (TO) and hexagon (Hexa) on the mechanical properties and deformation behaviors of the AlSi10Mg lattice structures were elucidated. TO lattice structure exhibited higher yield strength and plateau stress than the BCC and Hexa lattice structures. Shear band formation occurred in BCC and TO lattice structures during compression, resulting in the fluctuation of stress–strain curves. Continuous deformation behavior was observed in Hexa lattice structure without cracking of struts, which could be attributed to the low distributed Mises stress at tensile stress parts quantified by FEA. Hexa lattice structure exhibited small initial strain for densification. A large number of struts in compression direction led to the struts overlapping and early densification. TO lattice structure exhibited superior energy absorption capacity reaching the level of previously reported titanium alloy lattice structures. In addition, the results of high-speed indentation tests indicated that the practical energy absorption properties of TO and Hexa lattice structures can be estimated by static indentation tests.

In Chapter 3, the formation mechanism, process, preferential plane and direction of shear bands were clarified. It has been suggested that the shear band was triggered by the crack initiation and propagation at the tensile stressed regions in struts. Shear bands were preferentially formed on the densest plane including the most struts, when the loading axis was not parallel or perpendicular to this plane. The family of shear bands in BCC and FCC (octet-truss) lattice structure were in accordance with the slip system of the corresponding crystal structures. By thickening the center of struts and pruning the parts close to the nodes (low strut diameter ratios), the localized tensile stress in struts can be relieved according to the FEM analysis, suggesting low tendency of shear band formation. The effectiveness of this shear band suppression approach was demonstrated by the experimental results. The energy absorption capacity was substantially enhanced by suppression of shear band formation in the BCC lattice structures with optimized strut shape.

In Chapter 4, the lattice structures with a new configuration of C15-type unit cell inspired by the topologically close-packed structure of C15 Laves phase were established, on the basis of the consideration that the node and strut in lattice structure are analogous to the atom and atomic bond in crystal structure. The C15 lattice structures with various relative densities exhibited two plateau regions with graded stress level, enabling the structure to absorb high energy of 5.0 $MJ \cdot m^{-3}$. The two plateau regions in C15 lattice structures were attributed to the two different units of crisscross and deltahedron with graded relative density. Crisscross units preferentially exhibited a bending-dominated deformation behavior in 1st plateau, and subsequently deltahedron units exhibited a stretch-dominated deformation behavior in 2nd plateau, suggesting the hybrid deformation mode of C15 lattice structures. This result demonstrated the feasibility of controlling multi-plateau stress of TCP-inspired lattice structures composed of different coordinated polyhedron units. Imitating crystal structures have offered new avenues to design lattice structures with unique performance.

In Chapter 5, the hybrid lattice structure composed of differently arranged BCC and FCC unit cells were examined with comparison to homogeneous BCC and FCC lattice structures. The spatial arrangement patterns of BCC and FCC unit cells in hybrid lattice structures significantly influenced the mechanical properties and deformation behavior. The experimental yield strengths of all the hybrid lattice structures exceeded the upper-bound of prediction value of the Voigt model. Shear bands associated with stress drops appeared in Parallel hybrids, due to higher concentrated Mises stress at tensile stressed parts. The discontinuity of struts on the preferential shear band plane caused by the presence of different unit cell contributed to avoid shear band formation in Vertical and 3-dimensioal hybrid lattice structures. Therefore, appropriate arrangement pattern of different unit cells can achieve high plateau stress level without the stress loss by shear band formation, indicating high energy absorption capacity.

In Chapter 6, the main conclusions of this study were summarized and future prospects as a potential extension of the current research were presented. The unit cell type exhibited significant effect on the compressive behavior of lattice structures. Most elements showing high and uniform Mises stress resulted in high stiffness and plateau stress. The initiation of shear band formation was attributed to the cracks generated on the tensile stress parts of the strut owing to stress concentration. Relaxation of concentrated stress in struts and high Mises stress distributed on node contributed to the suppression of shear band. The lattice structure inspired by the C15 Laves phase exhibited hybrid deformation mode and can absorb high energy in two plateau stress levels. Hybrid lattice structure with appropriate arrangement pattern of different unit cells can enhance the energy absorption capacity because of high strength and successive deformation behavior. Therefore, a continuous improvement on the mechanical property was achieved by the proposed design strategies in this thesis. The strut shape optimization and hybrid approaches can be applied to high-strength lattice structures for further mechanical enhancement. By integrating the presented approaches, a multi-scale design strategy from the level of strut, unit cell, and arrangement was proposed as future prospect to maximize the mechanical properties and broaden the functionalities of lattice structures.