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A QUALITATIVE COMPARISON OF DIMENSIONAL DEVIATION OF LASER POWDER BED FUSION PROCESSED MULTI MORPHOLOGY LATTICE STRUCTURES BASED ON THERMOMECHANICAL SIMULATIONS

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Keywords

Fusion method, multi morphology, lattice structure, dimensional deviation, thermomechanical simulation

Abstract

Multi morphology lattices are composite lattice structures formed by different types of lattice structures in different configurations based on engineering application needs. These types of lattices can be manufactured with additive manufacturing modalities, specifically laser powder bed fusion process. However, due to the high cost and time spent on manufacturing these components, it is necessary to predict the properties of manufactured parts before build with numerical methods. This study focused on prediction of dimensional deviation of laser powder bed fusion produced multi morphology lattice structures composed of Schoen Gyroid, Schwarz Diamond, Schwarz Primitive, Schoen FRD and Neovius topologies via thermomechanical simulations qualitatively. Since the comparisons were made based on numerical study results, only qualitative assessments were performed. Among multi morphology lattices investigated in the present study, Schoen FRD topology at the center and Schwarz Primitive topology at the outer region showed the lowest deviations and Schoen FRD topology at the center and Schwarz Diamond topology at the outer region showed the highest deviations. It was also shown that adding Schoen FRD or Schwarz Primitive topologies at the outer region reduces the max. deviations, and Schoen Gyroid or Schwarz Diamond topologies increases the max. deviations.

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LAZER TOZ YATAĞI FÜZYON YÖNTEMI ILE ÜRETILMIŞ ÇOKLU MORFOLOJI KAFES YAPILARININ BOYUTSAL SAPMASININ TERMOMEKANIK SIMÜLASYONLARA BAĞLI NITELIKSEL BIR KARŞILAŞTIRMASI

Anahtar Kelimeler

Füzyon yöntemi, çoklu morfoloji, kafes yapısı, boyutsal sapma, termomekanik simülasyon

Öz

Çoklu morfoloji kafes yapılar, mühendislik uygulama ihtiyaçlarına göre farklı konfigürasyonlardaki farklı tipteki kafes yapılarının oluşturduğu kompozit kafes yapılarıdır. Bu tip kafesler, başta lazer toz yatağı füzyon prosesi olmak üzere, eklemeli imalat yöntemleriyle üretilebilir. Ancak bu bileşenlerin imalatında harcanan yüksek maliyet ve zaman nedeniyle, üretilen parçaların özelliklerinin imalattan önce sayısal yöntemlerle tahmin edilmesi gerekmektedir. Bu çalışma, lazer toz yatağı füzyon prosesi ile üretilen Schoen Gyroid, Schwarz Diamond, Schwarz Primitive, Schoen FRD ve Neovius topolojilerinden oluşan çoklu morfoloji kafes yapılarının boyutsal sapmasının termomekanik simülasyonlar yoluyla niteliksel olarak tahmin edilmesine odaklanmıştır. Karşılaştırmalar sayısal çalışma sonuçlarına göre yapıldığından sadece niteliksel değerlendirmeler yapılmıştır. Bu çalışmada incelenen çoklu morfoloji kafes yapılar arasında, merkezde Schoen FRD topolojisi ve dış bölgede Schwarz Primitive topolojisi olan yapı en düşük sapmaları gösterirken, merkezde Schoen FRD topolojisi ve dış bölgede Schwarz Diamond topolojisi olan yapı en yüksek sapmaları göstermiştir. Ayrıca dış bölgeye Schoen FRD veya Schwarz Primitive topolojilerinin eklenmesinin azami sapmaları azalttığı, Schoen Gyroid veya Schwarz Diamond topolojilerinin eklenmesinin ise azami sapmaları arttırdığı gösterilmiştir.

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1. Introduction

Triply periodic minimal surface (TPMS) lattice structures are one of a kind structures which can be modelled by mathematical expressions and contain unit cells with periodic and regular arrangements (Yin, Zhang, Zhu, Meng, Liu and Wen, 2023). Due to their high energy absorption, specific strength, acoustic and thermal behaviors, these structures are nowadays used in different industrial applications (Ataollahi, 2023). Schoen Gyroid, Schwarz Diamond, Schwarz Primitive, Schoen FRD and Neovius topologies (Figure 1) are types of TPMS structures which show different mechanical behaviors under axial loading conditions. Schwarz Primitive structures show stretch-dominated, and Schoen Gyroid and Schwarz Diamond structures show bending-dominated behavior under axial loadings (Gülcan, Simsek, Cokgunlu, Özdemir, Şendur and Yapici, 2022). Therefore, based on the need for related industrial applications, one of these geometries can be used. However, in applications where multiple loading conditions are effective, a combination of these lattices, called multi morphology lattices, needs to be used (Ma, Song, Lan and Ma, 2020). Due to the improved techniques in computer aided design software, different combinations of lattices can be modelled (Yang, Tian and Zhang, 2015). The manufacturing of these multi morphology lattices can be costly and time consuming or sometimes impossible, but due to the advancements in different additive manufacturing (AM) modalities, it is now easier to produce these parts from different material alternatives (Maconachie, Leary, Lozanovski, Zhang, Qian, Faruque and Brandt, 2019).

In scientific literature, different TPMS based multi morphology lattices were used in terms of enhancing the mechanical properties of the related application. Al-Ketan, Lee, Rowshan and Abu Al-Rub's (2020) experimental and numerical study revealed that multi-morphology lattices have different deformation mechanisms under compressive loading than conventional TPMS lattices. Xu, Mendola, Razavi and Bagherifard. (2023) investigated the mechanical properties of multi morphology lattices from Schoen Gyroid and Schwarz Primitive structures in different directions and stated that the arrangement of lattices has considerable effect on the final mechanical properties. Xi, Zhou, Zhang, Huang and Xiao (2023) designed multi morphology lattices from Schoen Gyroid, Schwarz Primitive and Neovious structures and based on experimental and numerical results, they stated that multi morphology lattices have multi-level energy absorption and multi-stage yield behavior when compared with conventional TPMS lattices. Novak, Al-Ketan, Borovinšek, Krstulović-Opara, Rowshan, Vesenjak and Ren (2021) investigated the mechanical properties of multi morphology lattices composed of Schoen Gyroid and Schwarz Diamond lattices in longitudinal and radial directions. They stated that under compressive loading, progressive characteristics can be obtained for longitudinally arranged lattices and constant characteristic can be obtained for radially arranged lattices in plateau region. Ozdemir, Simsek, Kiziltas, Gayir, Celik and Sendur's (2023) experimental study revealed that multi morphology lattices have higher stiffness than Schwarz Diamond or Schwarz Primitive single lattice morphologies.

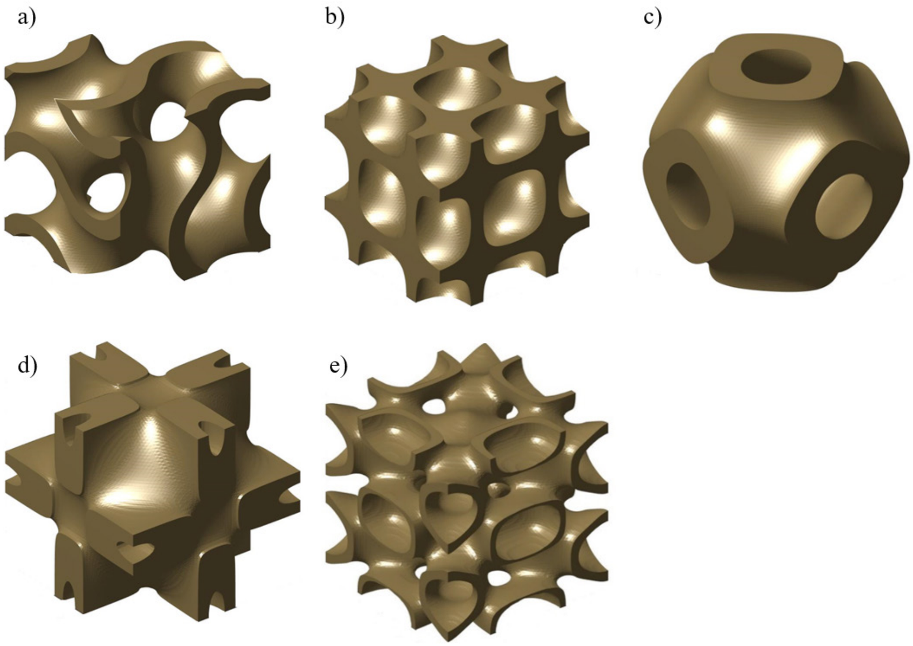

Figure 1. a) Schoen Gyroid, b) Schwarz Diamond, c) Schwarz Primitive, d) Neovius, e) Schoen FRD

Laser powder bed fusion (LPBF) is one of the AM processes where metal powders are deposited on a build platform layer by layer and selectively melted by using laser energy. When one layer is melted according to CAD geometry, build platform is lowered with an amount of layer thickness, then new metal powder layer is deposited onto the previous one and this process continues until the part is fully built (Sefene, 2022). LPBF method enables the manufacturing of multi morphology lattices however it has some drawbacks one of which is the high dimensional deviation during manufacturing due to differences in the powder particle size and the heat transfer from the melt pool to the surrounding powder (Bartolomeu, Dourado, Pereira, Alves, Miranda and Silva, 2020), adhesion of the powder to the surface due to the heat transfer between the powder and the solid part (Bartolomeu, Fonseca, Peixinho, Alves, Gasik, Silva and Miranda, 2019; Ran, Yang, Hu, Shen, Yu, Xiang and Cai, 2018; Sing, Miao, Wiria and Yeong, 2016; Wang, Wu, Bai, Li, Yang and Song 2017), stair step effect (Maconachie et al., 2019), conversion from CAD file to stl file (Calignano, 2018).

As can be seen from the existing literature, most of the studies related with AM or specifically LPBF manufactured multi morphology lattices focuses on their mechanical properties, not their dimentional deviations. To address this issue, in the present study, the main focus is dimensional deviation prediction of these type of lattices before LPBF built while obtaining the optimum mechanical properties based on the application needs. LPBF manufacturing and testing of multi morphology lattice structures is a costly and time-consuming process. To eliminate this, thermal and mechanical simulation based finite element modelling, or thermomechanical modelling (Denlinger, Gouge, Irwin and Michaleris, 2017) is used in the present study.

The rest of the paper is organized as follows. Lattice geometries, design of experiment, thermomechanical simulation details are explained in Section 2. The findings are presented in Section 3 and detailed discussions were also given by comparing the multi morphology lattices with conventional TPMS lattices. The summary and main conclusions were presented in the Conclusion section.

2. Materials and Methods

In this section, specimen geometry, design of experiment and thermomechanical simulation details are given. Research and publication ethics were complied in the present study.

2.1 Specimen geometry and design of experiment preparation

TPMS lattice geometries were modelled with our in-house developed software. The general 2D view of multi morphology lattices is shown in Figure 2. In region 1 and region 2, different types of TPMS lattices were used. All lattices have 6 mm unit cell size, 25 % volume fraction. The outer dimensions of region 1 and region 2 are 18 mm and 36 mm, respectively. Therefore, 3 and 6 unit cells were used in region 1 and region 2, respectively. By selecting these parameters, the min. wall thickness came out to be 0.5 mm. Schoen Gyroid, Schwarz Diamond, Schwarz Primitive, Schoen FRD and Neovius lattices were used in region 1 and region 2. Therefore, a total of 25 different specimens were designed. Section view of some of the multi morphology lattices are shown in Figure 3. The design of experiment is shown in Table 1.

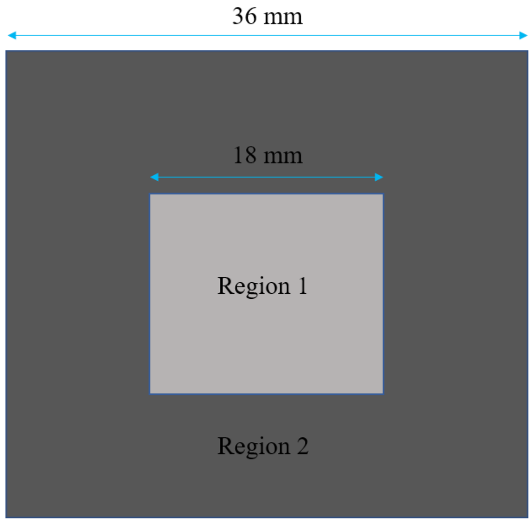

Figure 2. The Specimen Geometry and General Dimensions

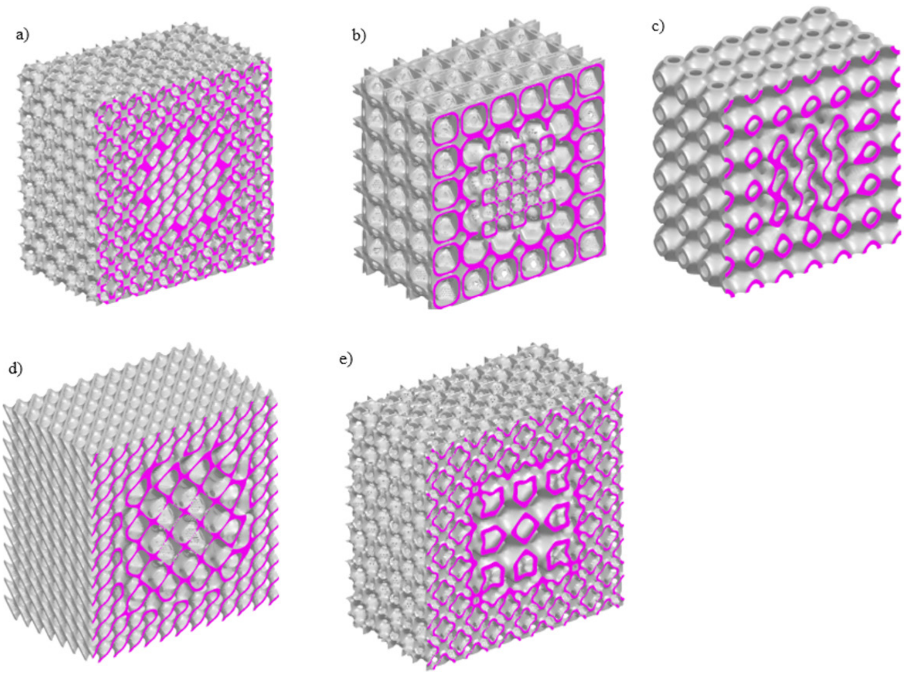

Figure 3. Multi Morphology Lattices with a) Schwarz Diamond - Schoen FRD, b) Schoen FRD – Neovius, c) Schoen Gyroid - Schwarz Primitive, d) Neovius - Schwarz Diamond, e) Schwarz Primitive - Schoen FRD

2.2 Thermomechanical simulation and mesh convergence study

Due to the high energy input from the laser to the powder bed, a very rapid and high heating is observed during melting phase. If a new powder layer is spread onto the previous one, then rapid cooling and solidification are observed. This rapid heating and cooling cycle results in residual stress formation in the part. These residual stresses may cause part distortion or cracks in the final geometry (Fergani, Berto, Welo and Liang, 2017). Trial and error printing can be used to mitigate these issues. However, these experimental approaches are time consuming and expensive. Therefore, thermomechanical simulations can be used to predict these residual stresses and final distortion and/or cracks before print which can mitigate the cost and time spent for iterative manufacturing processes (Denlinger, 2015).

In the present study, Simufact Additive 4.1 commercial software was used for thermomechanical numerical analysis of the LPBF process. Simufact Material library and CoCrMo alloy powder was used during simulation. CoCrMo material was selected in this study because it has outstanding toughness, corrosion resistance, high strength and wear resistance characteristics and used in different industrial applications (Gülcan et al., 2022).

In thermomechanical simulations, it is important that meshes need to capture fine geometrical details in the part. Meshes with very small size are good at prediction with high accuracy. However, in this case, computational time would be higher. Therefore, a mesh convergence study was performed by considering prediction accuracy and computational time. Specimen 1 and 5 different mesh sizes (0.7, 0.6, 0.5, 0.4, 0.3 and 0.2 mm) were evaluated. Dimensional deviation vs mesh size is shown in Figure 4. It is clear that after 0.3 mm mesh size, the diplacement value converges to a constant value. Therefore, rest of the simulations were performed by selecting 0.3 mm mesh size. Each simulation took 15 hours to complete. Meshes for one of the specimens (specimen 3) are shown in Figure 5.

Table 1. Design of Experiment Used in the Present Study

Specimen no	Geometry used in region 1	Geometry used in region 2
1	Schoen Gyroid	Schoen Gyroid
2	Schoen Gyroid	Schwarz Diamond
3	Schoen Gyroid	Schwarz Primitive
4	Schoen Gyroid	Neovius
5	Schoen Gyroid	Schoen FRD
6	Schwarz Diamond	Schwarz Diamond

7	Schwarz Diamond	Schoen Gyroid
8	Schwarz Diamond	Schwarz Primitive
9	Schwarz Diamond	Neovius
10	Schwarz Diamond	Schoen FRD
11	Schwarz Primitive	Schwarz Primitive
12	Schwarz Primitive	Schoen Gyroid
13	Schwarz Primitive	Schwarz Diamond
14	Schwarz Primitive	Neovius
15	Schwarz Primitive	Schoen FRD
16	Neovius	Neovius
17	Neovius	Schoen Gyroid
18	Neovius	Schwarz Diamond
19	Neovius	Schwarz Primitive
20	Neovius	Schoen FRD
21	Schoen FRD	Schoen FRD
22	Schoen FRD	Schoen Gyroid
23	Schoen FRD	Schwarz Diamond
24	Schoen FRD	Schwarz Primitive
25	Schoen FRD	Neovius

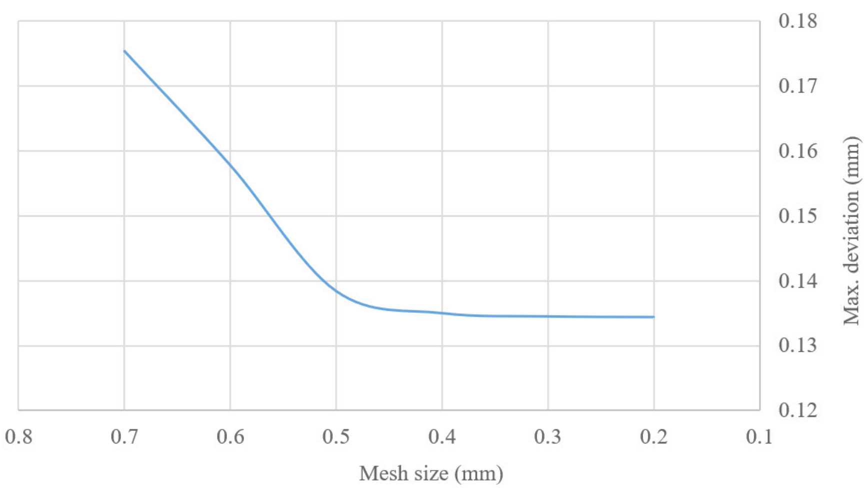

Figure 4. Mesh Convergence Study

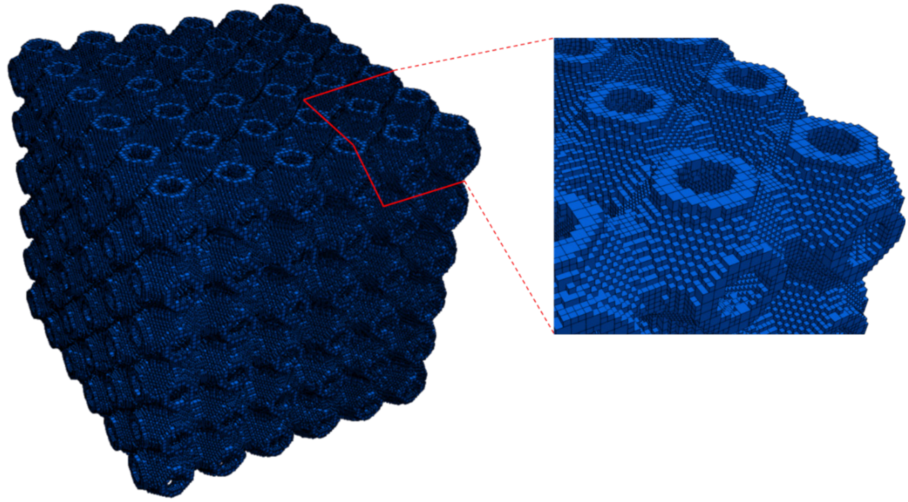

Figure 5. Meshes Applied to Specimen 3.

3. Results and Discussions

3.1 Single TPMS lattices morphologies

The max. deviations for different single TPMS lattices morphologies are shown in Figure 6. It is clear that Schoen FRD geometry showed the lowest (0.138 mm) and Schwarz Diamond showed the highest (0.281 mm) max. deviations. The different dimensional deviation results can be attributed to the different cross sectional areas of these lattices. Different cross sectional areas result in different energy input to these areas to melt the related cross section via laser energy which, at the end, causes different thermal deviations between successive layers and finally different dimensional deviations (Gülcan, Simsek, Özdemir, Günaydın and Tekoğlu 2024).

3.2 Multi morphology TPMS lattices with Schoen Gyroid at the center

Max. deviations for multi morphology TPMS lattices with Schoen Gyroid at the center are shown in Figure 7. For this combination (Schoen Gyroid at the center), the highest (0.251 mm) and the lowest (0.156 mm) max. dimensional deviations were observed when outer geometry is Schwarz Diamond and Schoen FRD, respectively. It is clear that when compared with single Schoen Gyroid specimens, multi morphology lattices with Schoen Gyroid at the center have higher max. deviations when Schwarz Diamond or Neovius topologies are added to the outer surfaces and have lower max. deviations when Schoen FRD or Schwarz Primitive topologies are added to the outer surfaces.

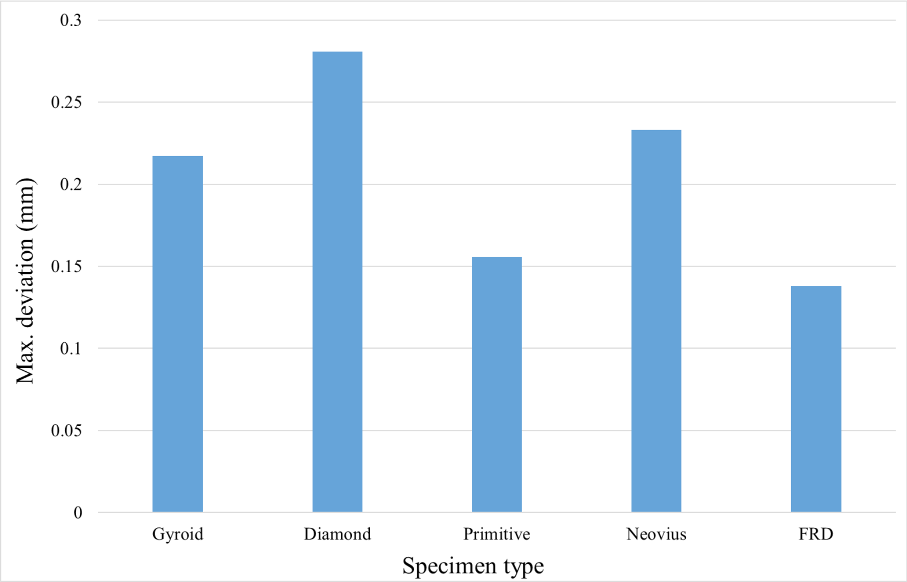

Figure 6. Max. Deviations for Different Single TPMS Lattices Morphologies

3.3 Multi morphology TPMS lattices with Schwarz Diamond at the center

Max. deviations for multi morphology TPMS lattices with Schwarz Diamond at the center are shown in Figure 8. It is clear that multi morphology lattice with Schwarz Primitive at the outer region and Schwarz Diamond at the center showed the lowest max. deviation (0.167 mm). On the other hand, single morphology lattice with Schwarz Diamond both at the center and at the outer region showed the highest max. deviation (0.281 mm). It can be concluded that in a multi morphology lattice with Schwarz Diamond at the center, all the TPMS topologies other than Schwarz Diamond at the outer region will reduce the max. deviation. Therefore, to obtain higher quality multi morphology parts with less deviation from the original geometry in LPBF process, Schwarz Diamond both at the center and at the outer region should not be preferred along with consideration of mechanical properties of printed parts for the related application.

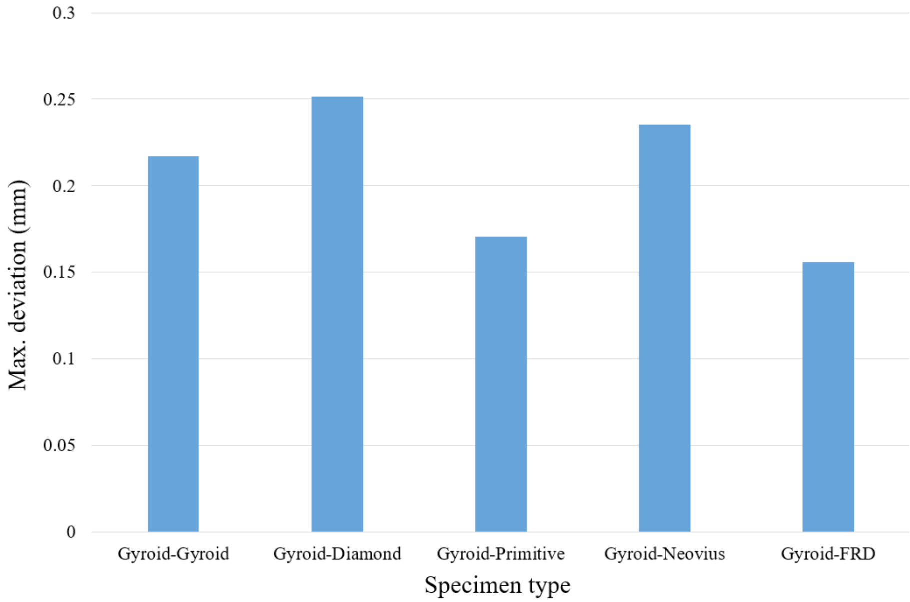

Figure 7. Max. Deviations for Multi Morphology TPMS Lattices with Schoen Gyroid at the Center

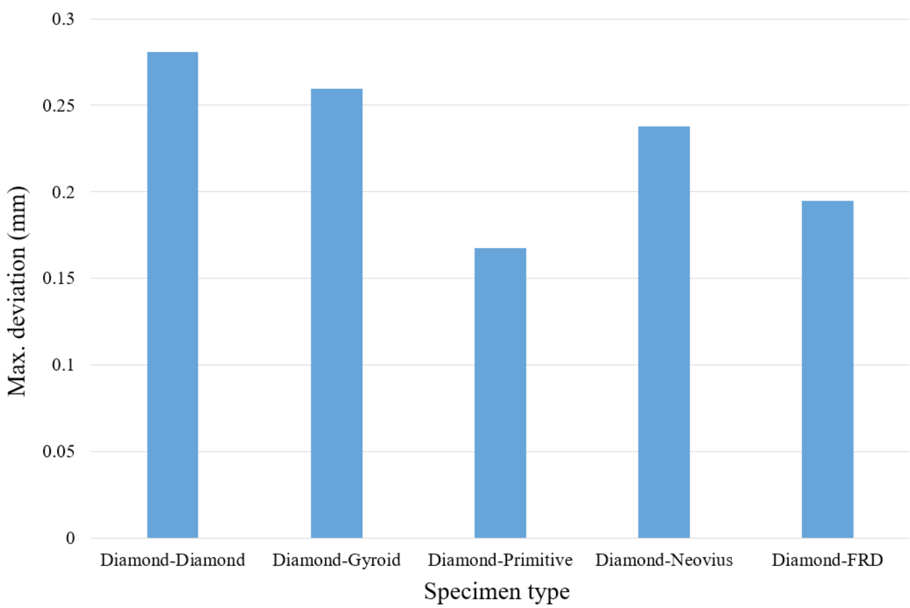

Figure 8. Max. Deviations for Multi Morphology TPMS Lattices with Schwarz Diamond at the Center

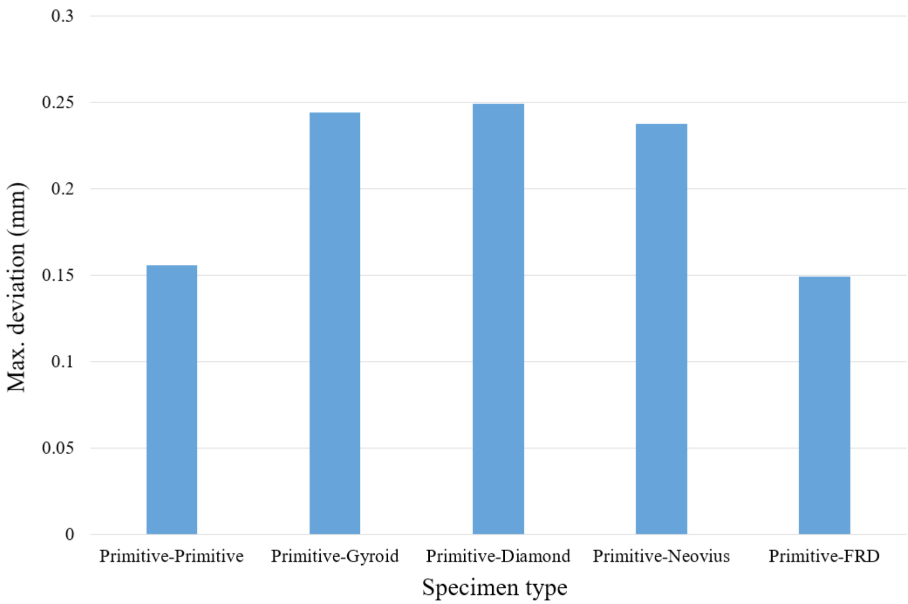

Figure 9. Max. Deviations for Multi Morphology TPMS Lattices with Schwarz Primitive at the Center

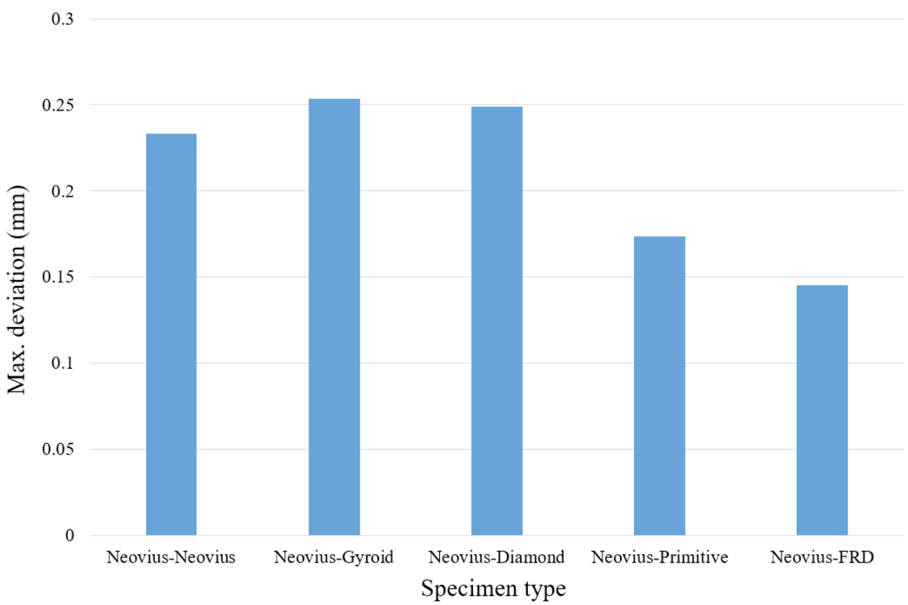

Figure 10. Max. Deviations for Multi Morphology TPMS Lattices with Neovius at the Center

3.6 Multi morphology TPMS lattices with Schoen FRD at the center

Max. deviations for multi morphology TPMS lattices with Schoen FRD at the center are shown in Figure 11. For this combination (Schoen FRD at the center), the highest (0.290 mm) and the lowest (0.138 mm) max. dimensional deviations were observed when outer geometry is Schwarz Diamond and Schoen FRD, which makes it single topology lattice, respectively. It is clear that when compared with single Schoen FRD specimens, multi morphology lattices with Schoen FRD at the center have higher max. deviations when all the other TPMS topologies are added to the outer surfaces. Therefore, it can be concluded that Schoen FRD topology should be preferred both at the center and at the outer region as much as possible to obtain the lowest amount of deviations considering the related application needs.

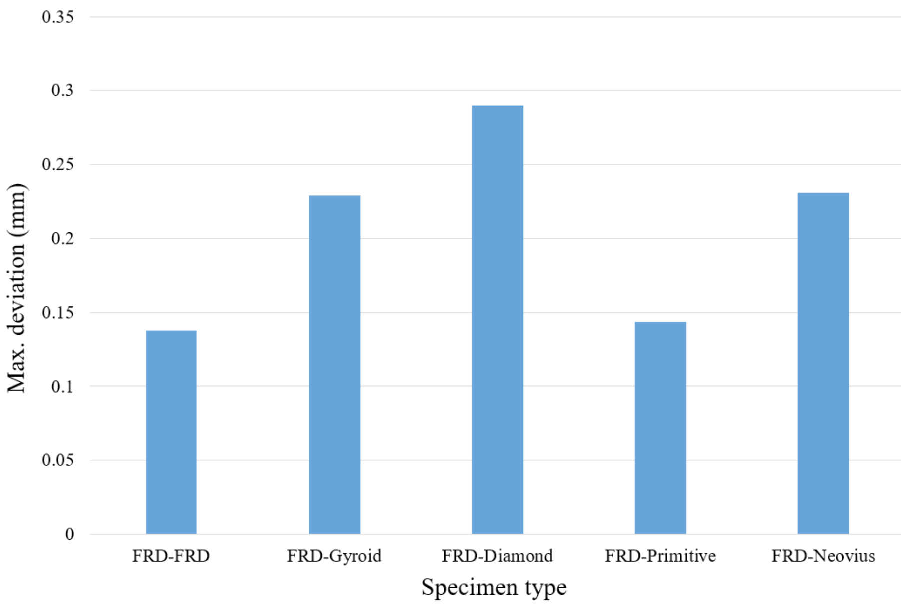

Figure 11. Max. Deviations for Multi Morphology TPMS Lattices with Schoen FRD at the Center

4. Conclusions

In the present study, dimensional deviation of multi morphology lattices produced by LPBF method were investigated by using thermomechanical simulations. A total of 25 different multi morphology lattices with two regions were designed and dimensional deviation of these lattices after LPBF process were evaluated and compared. Since the comparisons were made based on numerical study results, only qualitative assessments were performed. The quantitative assessments based on experimental data are left to a future work. Based on the numerical findings, the below main conclusions can be drawn:

In terms of single morphology lattices, Schoen FRD geometry outperformed by showing the lowest deviation (0.138 mm). On the other hand, Schwarz Diamond showed the worst deviation performance (0.281).

Among multi morphology lattices with different lattice topologies at the two regions, Schoen FRD topology at the center and Schwarz Primitive topology at the outer region showed the lowest deviations (0.143 mm). On the other hand, Schoen FRD topology at the center and Schwarz Diamond topology at the outer region showed the highest deviations (0.290 mm).

In general, it was observed that whatever the TPMS topology is at the center, adding Schoen FRD or Schwarz Primitive topologies at the outer region reduces the max. deviations.

In general, it was observed that whatever the TPMS topology is at the center, adding Schoen Gyroid or Schwarz Diamond topologies at the outer region increases the max. deviations.

This study considered only the dimensional deviation of multi morphology lattices. This is an important issue for these types of lattices during industrial applications. However, the mechanical behavior of these lattices is also very important. Therefore, future studies will focus on compression testing and mechanical behavior characterization of multi morphology lattices.

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