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**ANALYSIS OF CORRELATION BETWEEN MANUFACTURING PARAMETERS AND
MECHANICAL STRENGTH FOLLOWED BY UNCERTAINTY PROPAGATION OF
GEOMETRIC DEFECTS IN LATTICE STRUCTURES**

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ABSTRACT

Lattice structures are widely used in various applications, especially in aeronautic, aerospace, and medical applications because of their suitable properties. Thanks to advancement of the additive manufacturing technology, the lattice structures can be manufactured by different methods such as laser beam melting technology. However, the presence of geometric defects in the lattice structures is inevitable due to the manufacturing process. The geometric defects may have high impact on the mechanical strength of the structures. The geometric defects are directly linked to the process parameters. This paper presents the analysis of the correlation between the process parameters and the mechanical strengths. In addition, the uncertainty propagation of the mechanical strengths according to the process parameters is also studied.

Keywords: Additive manufacturing, lattice structure, geometric defects, design of experiment, uncertainty propagation.

1. INTRODUCTION

The presence of lattice structures is increasing in the manufacturing fields especially in the aeronautics, spacecraft and biomedical applications due to their advantages of high strength-to-weight ratios, energy absorption, acoustic and vibrational damping. Moreover, their stiffness and strength are controlled by their geometrical characteristics including the overall geometry of the lattice, its unit cell and the single strut element. Thanks to the advancements in additive manufacturing (AM), these structures have become very prominent in recent times due to their number of advantages including optimal use of material, shorter manufacturing time, reduced energy utilization and enhanced mechanical properties [1, 2]. These advantages make the lattice structures very suitable for aerospace, medical and engineering applications. Furthermore, they are also advantageous in context to the entire product life cycles, e.g., lattice structures are particularly beneficial in

minimizing material waste [3] and are able to be recycled easily, particularly when comprised of a single material. There are various types of lattice structures based on the composition of their unit cells. Helou et al. [1] categorized most of the lattice structures as manually and mathematically generated structures. In many cases of 3D-printing and especially additive manufacturing, the unit cell is composed of well-organized struts in various forms such as octet-truss, body centered cubic (BCC), body centered cubic with z struts (BCCz), face centered cubic (FCC), face centered cubic with z struts (FFCz), etc [4].

During the manufacturing process of a lattice structure, geometric defects are inevitably generated [5]. The defects can cause high impact on overall structural mechanical strength. It is necessary to be able to handle mechanical strength uncertainty according to process parameters. This work is based on a proposed simulation strategy [6] to predict mechanical strength variability.

In this work, two types of the lattice structures (body-centered cubic with z-struts (BCCZ) structures made of Inconel 718, and body-centered cubic (BCC) structures made of Scalmalloy are manufactured by selective laser melting machine using Taguchi design of experiment. Each structure is placed on the substrate with a specific position and orientation regarding the roller direction of deposited metal powder. The position and orientation are considered as the manufacturing parameters. The geometric defects of each beam in the lattice are characterized and used to build the geometric model in order to perform simulations. Then, the mechanical strengths are defined by the homogeneous response as structural rigidity and yield strength. The distribution of the mechanical strengths is observed as a function of manufacturing parameters. In addition, this work is carried out to study the uncertainty propagation of the geometric defects on the mechanical strength of the BCC lattice structure made of Scalmalloy. To do that, we observe the distribution of mechanical strengths of the lattice according to the distribution of the geometric defects. A probability density law is determined

based on a statistical hypothesis corresponding to the geometric defects of the inclined beams. The samples of inclined beams are then drawn from the density law to build the lattice structure samples. The lattice samples are then used for simulation to characterize the mechanical strengths.

2. EXPERIMENTAL DESIGN OF EXPERIMENT

Selective laser melting (SLM) is used to produce the lattice structure. Different process parameters such as laser position, intensity, speed and trajectory, Argon gas source and direction, roller source and direction can affect manufactured structures. In this study, we consider the manufacturing parameters as position (x,y) and orientation β of lattice structure relative to roller and Argon gas direction see figure 1. Eventually, the position and orientation parameters can be related to the aforementioned process parameters.

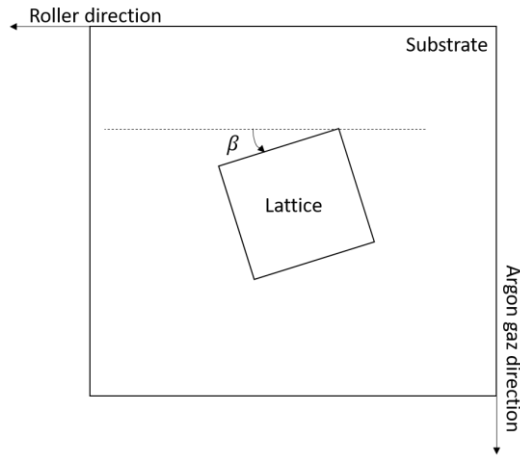


FIGURE 1: ORIENTATION OF A LATTICE STRUCTURE RELATIVE TO ROLLER AND ARGON GAS DIRECTION

In order to find the correlation between geometric defects and manufacturing parameters, we consider the orthogonal array design of experiment to reduce the number of manufactured lattices [7].

BCCz lattice structures of 3x3x3 made of Inconel 718 material are manufactured on the manufacturing substrate. Figure 2-a illustrates the design of experiment of nine structures A8KA01-09 on the substrate and three orientations of the structures relative to roller direction $\beta = -15^\circ, 0^\circ, 15^\circ$. Moreover, eight structures of BCC (LIDA01-08) 3x3x3 made of Scalmalloy material is also manufactured as shown in figure 2-b on the substrate and three orientations of the structures relative to roller direction $\beta = -15^\circ, 0^\circ, 15^\circ$.

A8AK03 15	A8AK06 0	A8AK09 -15
A8AK02 -15	A8AK05 15	A8AK08 0
A8AK01 0	A8AK04 -15	A8AK07 15

(a)

LIDA04 -15	LIDA06 0	LIDA02 15
LIDA01 0	LIDA05 15	LIDA03 -15
LIDA07 15	LIDA08 -15	

(b)

FIGURE 2: SPECIMENS MANUFACTURED ON THE SUBSTRATE (A) BCCZ A8KA01-09 (B) BCC LIDA01-08

3. GEOMETRIC DEFECT CHARACTERIZATION

Geometric defects can be characterized by elliptic shape obtained by ellipse fitting of the lattice cell strut cloud point projection on the plan orthogonal to the strut axis as shown in figure 3 [5]. The elliptic shape of each strut can be obtained in our platform LATANA (LATtice ANALyis) which is developed in a project framework at Institut de Recherche Technologique Systemx. The cloud points are obtained using CT-scan of the manufactured structures.

We consider geometric defects occurring on each beam of a lattice structure as an elliptic shape with semi major axis a , semi minor axis b , and angle as orientation of ellipse in the range $[-\frac{\pi}{2}, \frac{\pi}{2}]$ (see figure 4). The defects are defined as angle, area of the ellipse πab and its eccentricity $\sqrt{1 - (\frac{b}{a})^2}$.



(a)

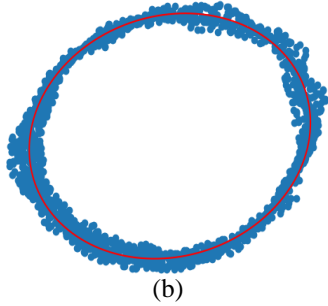


FIGURE 3: (A) CLOUD POINTS REPRESENT THE STRUT OF A LATTICE CELL (B) PROJECTION AND ELLIPSE FITTING OF CLOUD POINTS ON THE PLAN ORTHOGONAL TO THE STRUT AXIS

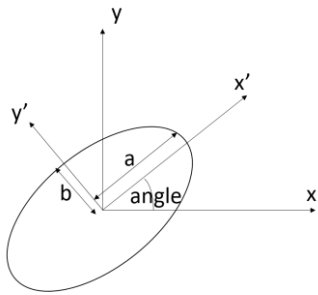


FIGURE 4: REORIENTED ELLIPSE

4. MECHANICAL MODELLING AND STRENGTH CHARACTERIZATION

4.1 Mechanical modelling

The lattice structure of the 3D model is under compressive load with imposed displacement $u = 1.5\text{mm}$ on top of the jaw and is clamped at the bottom of the jaw where the lattice structure is in contact with the top and bottom of the jaw (contact unilateral with the friction coefficient $\mu=0.3$) as shown in figure 6. The constitutive law is elastic plastic with multilinear isotropic hardening. Large deformation is considered in the modelling.

To reduce the computational time, the hybrid model is proposed for mechanical simulations. The hybrid model is composed of the beam element represent the strut of the lattice cell and the 3D element represent the junction joining between struts as shown in figure 6. The junction between the beam element and the 3D junction is the multipoint constraint. The simulations are performed in finite element solver ANSYS.

Hybrid model can be used thanks to the agreement between the 3D model and the hybrid model for the lattice structure taking into account the geometric defects (see figure 5). For more information on the hybrid model, the interested readers are referred to Ref. [8].

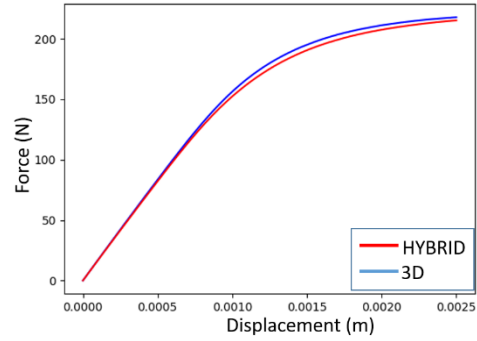


FIGURE 5: COMPARAISON BETWEEN HYBRID AND 3D MODEL

4.2 Mechanical strength characterization

The global response defined as the reaction force versus the imposed displacement of the lattice is used to characterize the mechanical strength of the lattice structure. We define the homogenous stress as $\sigma = \frac{F}{A}$ where F is the reaction force due to the imposed displacement u , and A is the area of the top surfaces of the lattice structure in contact with the substrate as shown in figure 7. The homogenous strain is defined as $\varepsilon = \frac{u}{L}$ where L is the height of the lattice structure. Global structural rigidity E and yield strength σ_e are calculated as indicators of the mechanical strength of the lattice structure in this study. Structural rigidity is determined as the slope of the linear regression of the first several points of the curve stress-strain as shown in figure 8. Yield strength is determined by the intersection of the slope of linear elastic of the curve stress-strain at $\varepsilon = 0.2\%$.

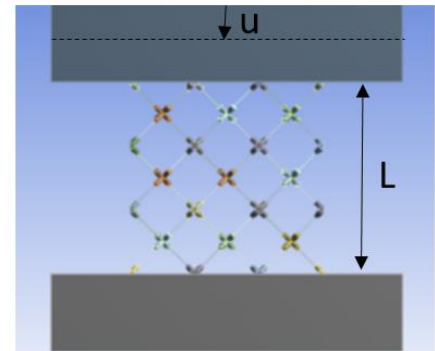


FIGURE 6: BOUNDARY CONDITIONS OF A HYBRID LATTICE STRUCTURE BETWEEN THE JAWS

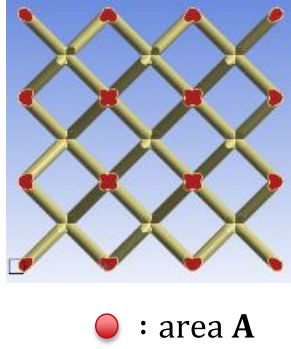


FIGURE 7: CONTACT AREA BETWEEN THE LATTICE STRUCTURE AND A JAW

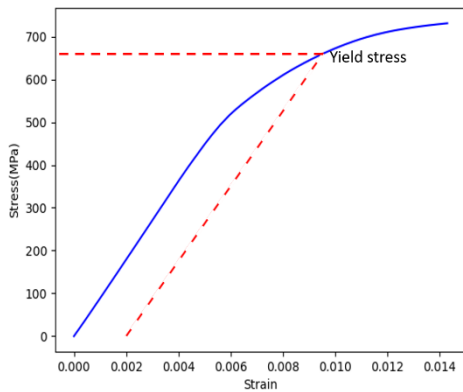


FIGURE 8: STRESS-STRAIN CURVE AND STRAIN AT 0.2%

5. UNCERTAINTY PROPAGATION OF LATTICE STRUCTURE BCC

5.1 Statistical hypothesis

We consider four classes of coaxial beams which are defined as the following pairs: (000,111); (100,011); (010,101); (001,110) (figure 9). Figure 10 illustrates distribution of oblique beams of the defect couples (area, eccentricity); (area, angle); and (eccentricity, angle) according to the four classes of the oblique beams. The four different colors correspond to four different classes. The dark and light of the same colors correspond to the coaxial beams. The repartition of dark and light colors of each beam is regrouped in the same class. Hence, the coaxial beams have the same statistical behavior. Therefore, we can consider distribution law according to each class of coaxial beams.

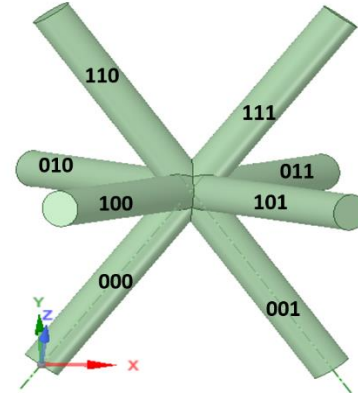


FIGURE 9: ORIENTATION OF STRUTS IN A LATTICE CELL

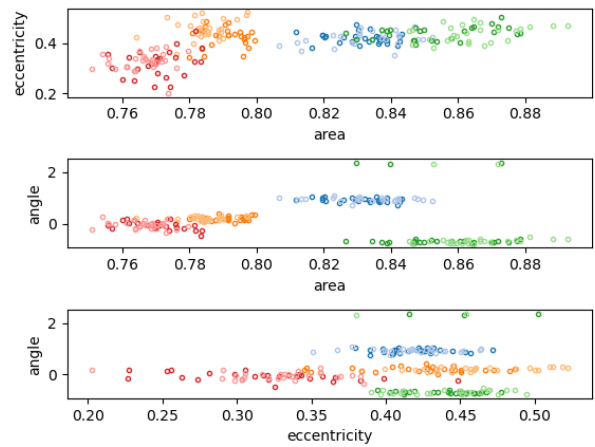
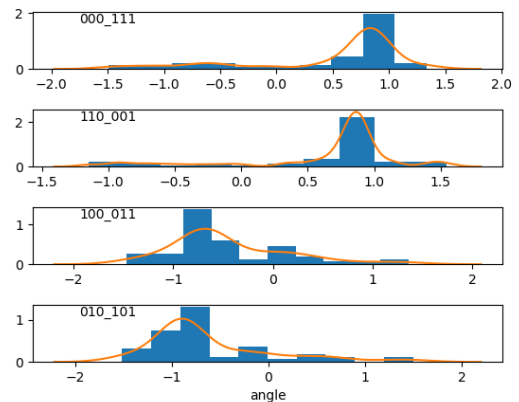


FIGURE 10: DISTRIBUTION OF COUPLE OF GEOMETRIC DEFECTS ACCORDING TO EACH STRUT OF A LATTICE STRUCTURE

In each coaxial beam class, density law is determined by kernel density estimate method [9] according to each defect parameter. Figure 11 shows the distribution law of each coaxial beam class corresponding to angle, area and eccentricity defects. These density laws are used to build samples of oblique beam in the following section.



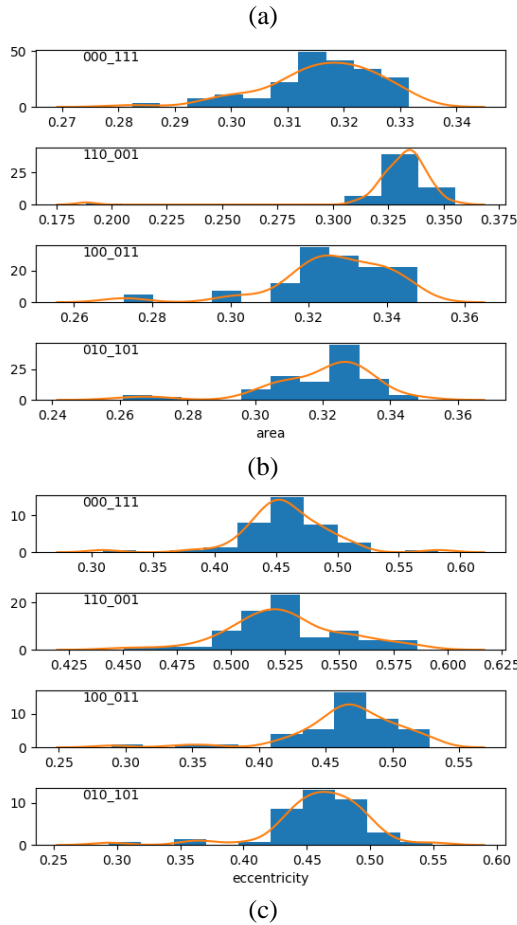


FIGURE 11: DISTRIBUTION LAW OF EACH COAXIAL BEAM CLASS FOR DIFFERENT GEOMETRIC DEFECTS

5.2 Sample generation

Figure 12 illustrates ten samples of each coaxial beam class according to different defects angle, area, and eccentricity respectively. The oblique beams are used to create samples of lattice structure. These samples allow to create numerical design of experiment to simulate the mechanical model in order to obtain the distribution of mechanical strength.

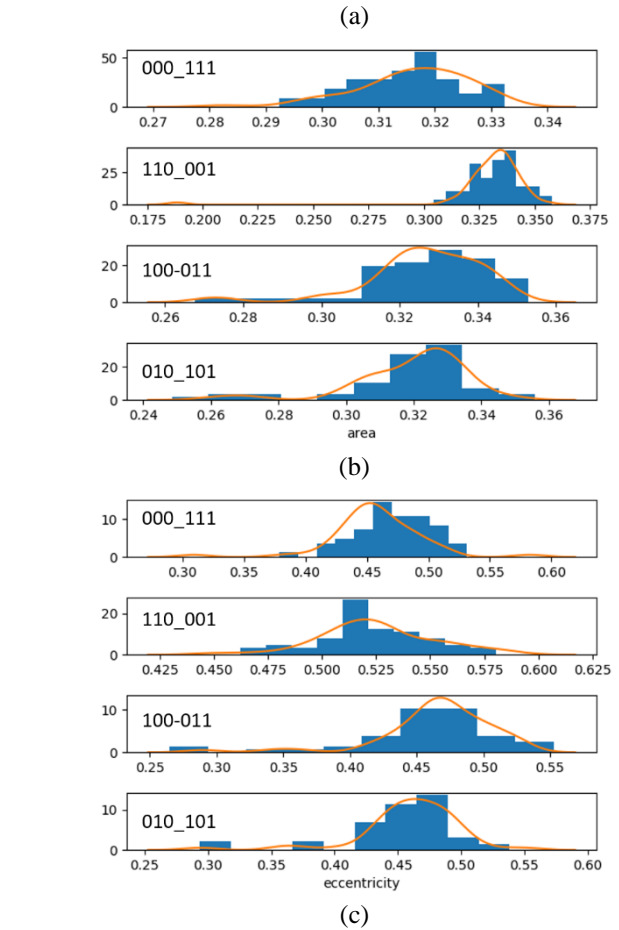
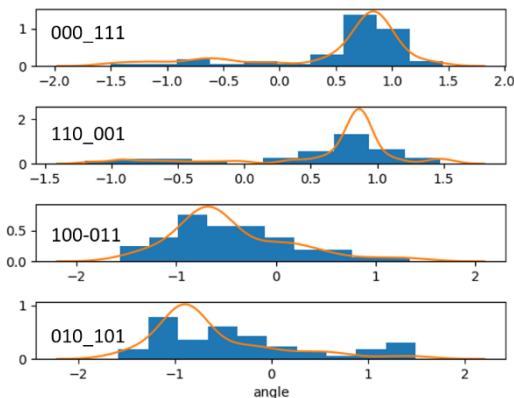


FIGURE 12: TEN SAMPLES DRAWN FROM A DISTRIBUTION LAW OF GEOMETRIC DEFECTS

5.3 Uncertainty propagation

The geometric defects in lattice structure are distributed according to the probability distributions of the coaxial beam classes as indicated in the previous section. The defect parameters (area, eccentricity and angle) in this case are uncertain parameters. With this set of uncertain parameters of the lattice structures, the mechanical strengths will be analyzed in order to study their distributions. Uncertainty propagation in this study refers to the propagation of the defect parameters to obtain the distribution of the mechanical strengths. The distributions of defects in this case refers to the variability of mechanical strength of the lattice structure on the substrate with the same manufacturing parameters. The variability of the mechanical strengths is thus to be analyzed on this structure.

6. RESULTS AND DISCUSSION

The following sections present the results of simulations of the lattice structures on the substrate for two types of materials. The correlation between the process parameters and the mechanical strength is analyzed. Then, the uncertainty propagation will be studied according to the variation of the mechanical strengths of the numerical lattice structure samples.

6.1 Correlation between mechanical strength and process parameters

6.1.1 Lattice structure BCCz

The nine specimens (A8KA01-09) on the substrate are simulated. Figure 13 illustrates homogenous responses of the nine structures and the nominal lattice in which geometric defects are not present. All homogenous responses of the structures underestimate the nominal homogenous response. This links to the fact that the defect areas of beams are smaller than the nominal area. The gap among experimental structures and nominal one are large according to their responses. The gap of the stress at the strain 1.4% is around 9%. But, the largest gap of the stress among the lattice structures at the strain of 1.4% is around 5%. The mechanical homogenous response of the defect lattices are less sensitive to the manufacturing parameters. This can be explained by the fact that the area defect of the vertical beams slightly changes on the substrate and the global response of the lattice BCCz under compression relies strongly on the vertical beams. Figure 14 illustrates the distribution of the mechanical strength (structural rigidity and yield strength) of each lattice structure on the substrate. The largest gap of structural rigidity among lattice structures is around 2.88%, and of yield strength is around 4.57%. This indicates that the manufacturing parameters have less influence on the mechanical strength.

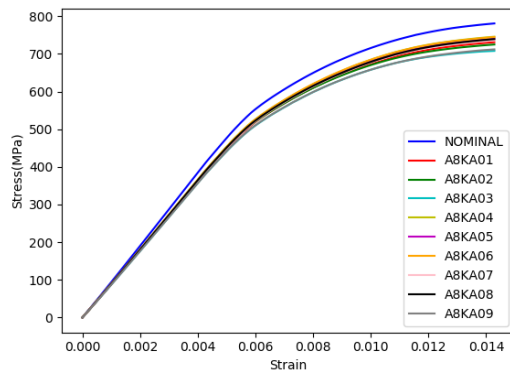
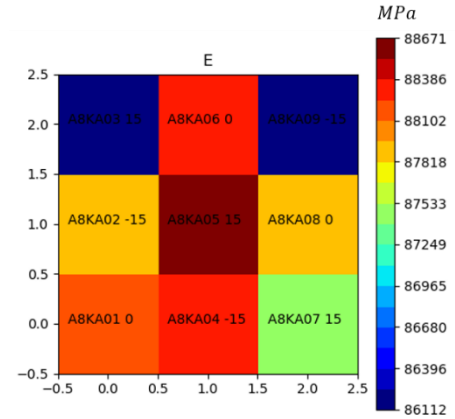
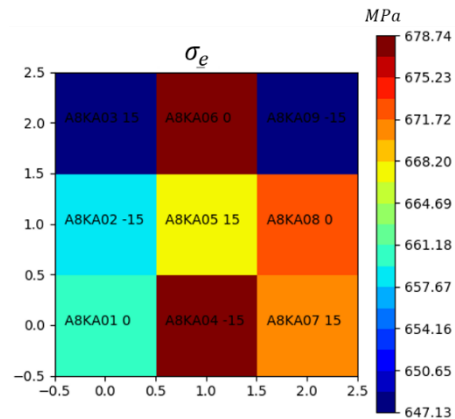


FIGURE 13: HOMOGENEOUS RESPONSES OF THE LATTICE STRUCTURES ON THE SUBSTRATE FOR BCCZ MADE OF INCONEL 718



(a)



(b)

FIGURE 14: MECHANICAL STRENGTH DISTRIBUTION (A) STRUCTURAL RIGIDITY (B) YIELD STRENGTH FOR BCCZ MADE OF INCONEL 718

6.1.2 Lattice structure BCC

Figure 15 illustrates homogenous responses of the LIDA01-08 and the nominal lattice. All homogenous responses overestimate the nominal homogenous response because the defect areas are larger than the nominal area. The gap between the structures with defects and the nominal one are large according to their responses. The largest gap of the stress at the strain of 6% is 13%. The mechanical homogenous response of the defect lattices are very sensitive to the manufacturing parameters.

Figure 16 illustrates the distribution of the mechanical strength of each lattice structure on the substrate. The rigidity of the structure is large at the center of the substrate due to large area defect at the center. The structure is more rigid when the structure is farther from the Argon gas and roller source as the area is larger. The largest gap of the structural rigidity among the structures is around 21%. This indicates that the manufacturing parameters have strong influence on the structural rigidity. For the same orientation β except the middle position, the gap between the structural rigidity is around 15%. For different orientations except the middle position, the gap between the

structural rigidity is around 10%. This indicates the influence of both manufacturing parameters has direct influence on structural rigidity. The structural rigidity is correlated directly to the area defect due to the manufacturing parameters. As in figure 16-b, the yield strength is inversely correlated to the structural rigidity, i.e. when the structural rigidity is larger, the yield strength is smaller. The largest gap of the yield strength among the lattice structure is around 18.6%. This indicates that the yield strength is also sensitive to the manufacturing parameters. From this analysis, the most rigid structure is the structure at the center of the substrate but with the lowest yield strength, and the structures that are more rigid with higher yield strength are those which are father from the Argon gas and roller sources. The table 1 illustrates the mean and the standard deviation of structural rigidity and yield strengths of all structures on the substrate. The standard deviation of structural rigidity is around 47 MPa relative to the mean value 609 MPa, which indicates the strong variation of structural rigidity. On the other hand, the standard deviation of the yield strength is small (1.55 MPa) relative to its mean value 20.25MPa, which indicates very low variation of the yield strengths. Later, we focus the study on the variation of the structural rigidity in the section of uncertainty propagation.

TABLE 1: MEAN AND STANDARD DEVIATION OF MECHANICAL STRENGTH OF LATTICE STRUCTURE BCC SCALMALLOY ON THE SUBSTRATE

	Mean	Standard deviation
Structural rigidity (MPa)	609.18	46.48
Yield strength (MPa)	20.25	1.55

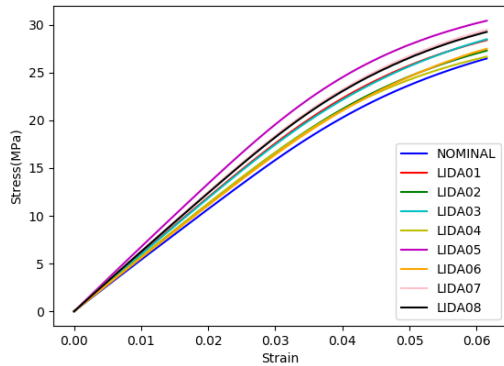
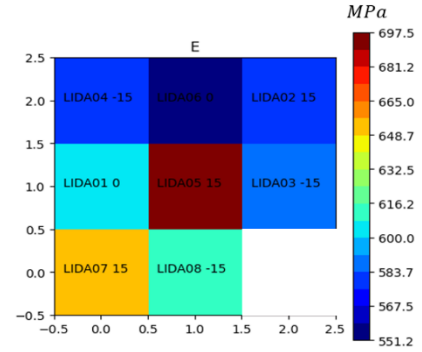
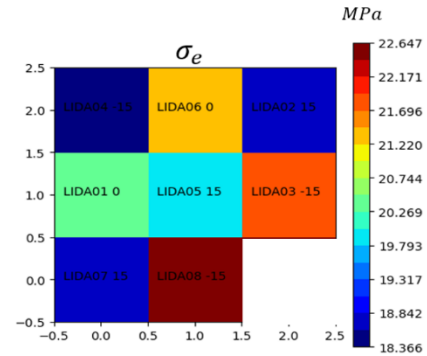


FIGURE 15: HOMOGENEOUS RESPONSES OF THE LATTICE STRUCTURES ON THE SUBSTRATE FOR BCC MADE OF SCALMALLOY



(a)



(b)

FIGURE 16: MECHANICAL STRENGTH DISTRIBUTION (A) STRUCTURAL RIGIDITY (B) YIELD STRENGTH FOR BCC MADE OF SCALMALLOY

6.2 Uncertainty propagation of lattice structure BCC

We consider an experimental specimen LIDA08. Ten samples of the specimen are generated. The samples are then simulated using the hybrid model thanks to the reduced computational time. Hence, the mechanical strength of each sample can be determined.

Because of the high dispersion in structural rigidity (as mentioned in the previous section), the distribution of the structural rigidity has to be considered. Table 2 shows the mean and standard deviation of structural rigidity of the samples. The distribution of density probability of the structural rigidity approaches the normal distribution with the mean and standard deviation ($\mu=613.7$, $s=16.1$) as shown in figure 17.

TABLE 2: MEAN AND STANDARD DEVIATION OF MECHANICAL STRENGTH OF LATTICE STRUCTURE SAMPLES BCC MADE OF SCALMALLOY

Structural rigidity (MPa)	Mean	Standard deviation
Samples	613.7	16.1

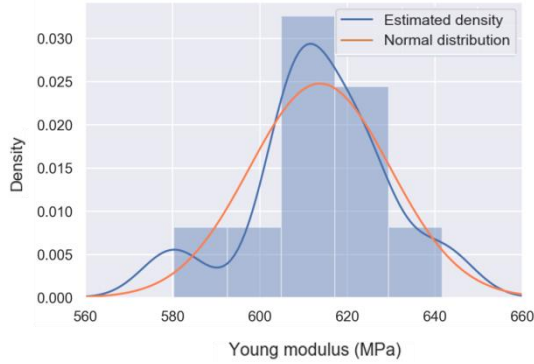


FIGURE 17: APPROXIMATED NORMAL DISTRIBUTION LAW OF STRUCTURAL RIGIDITY OF THE LATTICE STRUCTURE SAMPLES BCC MADE OF SCALMALLOY

In regard to the distribution of structural rigidity of the structures LIDA01-08, the mean and standard deviation ($\mu = 609.1, s = 46.48$) is estimated. And, the estimated density of this distribution approaches normal law as shown in figure 18.

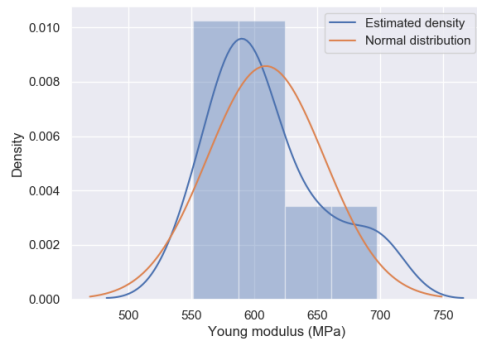


FIGURE 18: APPROXIMATED NORMAL DISTRIBUTION LAW OF STRUCTURAL RIGIDITY OF THE LATTICE STRUCTURES ON THE SUBSTRATE BCC MADE OF SCALMALLOY

Figure 19 illustrated the comparison of the normal law of the LIDA08 samples and the LIDA01-08 on the substrate. The dispersion of the structural rigidity of the LIDA01-08 is 3 times more than the structural rigidity of the LIDA08 samples. This shows the high variability of the structural rigidity according to the manufacturing parameters. However, the variability of the structural rigidity of the LIDA08 structure is not negligible.

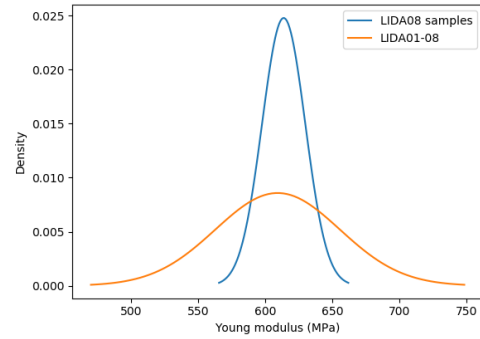


FIGURE 19: COMPARAISON OF THE DISTRIBUTION LAW BETWEEN THE LATTICE STRUCTURE SAMPLES AND ON THE SUBSTRATE

7. CONCLUSIONS

Taguchi design of experiment of BCCz lattice structures made of Inconel 718 and BCC lattice structures made of Scalmalloy for experiments was carried out to analyze the correlation between process parameters (position and orientation of the specimen on the substrate) and mechanical strengths. Geometric defects are characterized and measured using the in-house developed platform LATANA on cloud points extracted from CT-scan of the experimental specimens. In addition, mechanical simulations of the lattice structures with geometric defects are performed to characterize the mechanical strengths. Then, the correlation between the process parameters and the mechanical strength was analyzed. For the BCCz structures made of Inconel 718, the mechanical strengths are less sensitive to the process parameters because the mechanical strengths rely on the vertical beams and their geometric defects which slightly changes. On the other hand, for the BCC structures made of Scalmalloy, the process parameters have strong impact on the mechanical strength, mainly the structural rigidity. Uncertainty propagation is then carried out for the variation of structural rigidity according to the process parameters for BCC structures made of Scalmalloy. The results reveal that the distribution of mechanical strengths of the structures with the same manufacturing parameters are less dispersed than the one of the structures with different manufacturing parameters. Nevertheless, the dispersion of mechanical strengths due to the structures with the same manufacturing parameters are not negligible.

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