Analysis of the effect of porosity on the mechanical behaviour of L-PBF Inconel 718 using XRCT

A Pascual1,2*, N Ortega2, S Plaza2 and I Holgado1

1 Aeronautics Advanced Manufacturing Center, CFAA (UPV/EHU), Bizkaia Technology Park, Building 202, 48170 Zamudio, Spain
2 Faculty of Engineering of Bilbao, UPV/EHU, Plaza Torres Quevedo 1, 48013 Bilbao, Spain

*Corresponding author: alejandro.pascual@ehu.eus

Abstract: The scope of this work is to assess the influence of porosity on the mechanical behaviour of L-PBF Inconel 718. To this end, some test specimens were manufactured by L-PBF, according to ASTM E8/E8M. Afterwards, these specimens were scanned by means of XRCT in order to analyse the porosity of each one. The XRCT geometry generated by the previous step were used for FEM analysis. Finally, the results obtained by the analysis were correlated with the experimental results, highlighting the promising future of the proposed methodology.

Keywords: XRCT, Porosity, FEM, Inconel 718.

1. Introduction

Inconel 718 is a Nickel based alloy which presents high strength at high temperatures. For that reason, it is widely used in the aeronautical sector. However, the problems of non-conventional manufacturing processes, such as additive manufacturing, and the aeronautical security standards require a comprehensive assessment of the Inconel 718 components manufactured by these methods.

The unexpected appearance of defects during the manufacturing process of industrial components compromises their performance. These defects produce geometrical discontinuities, which yield stress concentrations around them and, thus, promoting the failure of the component driven by void growth and coalescence.

Regarding the stress concentrations produced by pores, the porosity percentage, pore size and distribution are some of the most common indicators. Nevertheless, there are some aspects such as pore shape, orientation, spacing and edge distance, which have an even greater influence [1]. In addition, the loading direction plays a major role in the effects of pores on stress concentrations [2,3].

Therefore, a proper estimation of these defects enables to make accurate predictions of the mechanical behaviour of the component by using this information for FEM analysis.

In this context, X-ray computerized tomography (XRCT) is increasingly being used as Non-Destructive Testing method (NDT), due to its ability to inspect internal and external features at the same time [4,5]. This advantage allows not only the qualitative analysis of defects, but also the quantitative one by dimensioning and locating each defect in the virtual reconstruction of the scanned workpiece. Moreover, this technique provides a 3D volume of the scanned workpiece, which could be used for several engineering applications such as dimensional metrology and quality control, reverse engineering or FEM analysis, amongst others.
Nonetheless, there are different methods to create a FEM model from XRCT data, which not always result in a straightforward way. The XRCT data is to be segmented to provide a polygon mesh model, commonly in a STL file format, or a binary volume of the scanned workpiece. Afterwards, these digitalized geometry and mesh is used to generate the FEM model of the scanned workpiece. To carry out this task, there are three main methods [6]:

- Hexahedral volume meshing from voxels of binary volume, which provides a brick model.
- Tetrahedral volume meshing from polygonal mesh surfaces, which demands more resources and the accuracy of the results depends on the mesh refinement.
- Meshing a CAD model generated from the XRCT data by means of reverse engineering solutions, which requires more effort than the previous options. When dealing with simple geometries, they could be approximated to basic CAD geometries. However, complex geometries require more complicated reverse engineering solutions [7]. Furthermore, the trustworthiness of the results obtained by the FEM analysis depends on the accuracy of the CAD model generated.

Therefore, this work focuses on workpiece scanning by XRCT, data processing for defect analysis and building a FEM model from the XRCT geometry. Finally, results obtained by the FEM analysis are correlated with experimental results under tensile stress conditions.

2. Methodology
According to the previous statement, the presented methodology is based on the coupling of XRCT and FEM. This method allows estimating the effects of different porosity aspects such as size, shape and spacing, based on the real porosity distribution of each component. The proposed methodology is presented in figure 1.

![Figure 1. General scheme of the proposed methodology.](image)

3. Experimental Procedure
In order to investigate these effects, four test specimens were designed according to ASTM E8/E8M, as shown in figure 2 and table 1. The first one was designed without pores, and the other three were defined with different homogeneous porosity distributions. For simplicity, the number of voids, shape and location of each pore remains constant. Only the pores size was modified in each test specimen. The
A schematic representation of void distributions is presented in figure 2. The characteristics of each one are detailed in table 2.

![Figure 2. Schematic representation of void distribution.](image)

**Table 1. Test specimen dimensions.**

| Units | D | R | A | L   | B   | C   |
|-------|---|---|---|-----|-----|-----|
| mm    | 9 | 8 | 54| 146.5 | 40  | 15  |

**Table 2. Test specimens void distribution.**

| Units   | Specimen 1 | Specimen 2 | Specimen 3 | Specimen 4 |
|---------|------------|------------|------------|------------|
| Voids shape | - | - | sphere | sphere |
| Voids diameter | mm | 1 | 0.8 | 0.3 |
| $S_V$ distance | mm | 4 | 4 | 4 |
| $S_H$ distance | mm | 2 | 2 | 2 |
| Number of voids | - | 40 | 40 | 40 |
| Porosity percentage $^a$ | % | 0.152 | 0.078 | 0.004 |

$^a$ Calculated in the region of interest

Test specimens were manufactured by Laser Powder Bed Fusion (L-PBF). For this purpose, a Renishaw AM400 manufacturing system (Renishaw, Wotton-under-Edge, UK) was utilized, using QuantAM software (Renishaw, Wotton-under-Edge, UK) for programming. The layer thickness was set at 60 µm and the laser paths were modified 67 degrees between layers. Regarding the building direction, the specimens main axis were set vertically. Finally, test specimens were blasted by the Guyson Euroblast 4 blasting machine (Guyson, Skipton, UK) with white corundum WSK 80 as blasting material.

For the scanning purpose, a General Electric X-Ray machine model X-Cube Compact (Baker Hughes, Houston, TX, USA) with 5 axes was used. The voltage and current limits of the XRCT system are 195kV and 8mA respectively and focus size small/large are 0.4/1mm. The scanning conditions by XRCT are summarized in table 3. VGStudio MAX 3.4 (Volume Graphics, Heidelberg, Germany) software was used for XRCT data processing. VGEasyPore algorithm was utilized for porosity analysis.

**Table 3. Scanning conditions by XRCT.**

| Focal spot size (mm) | Hardware filters | Voltage (kV) | Current (mA) | Exposure time (ms) | Projections | Magnification |
|----------------------|------------------|--------------|--------------|--------------------|-------------|--------------|
| 0.4                  | 1mm Cu and 0.5mm Sn | 195          | 2.2          | 100                | 720         | 2.231        |

The real geometry obtained by XRCT was used for FEM virtual tensile testing. To this end, the XRCT polygonal mesh surfaces were processed by MATLAB R2020a software (MathWorks, Natick,
MA, USA) in order to achieve the tetrahedral volume mesh of each specimen. Finally, the FEM analysis was carried out by ABAQUS 6.14 software (Dassault Systèmes SE, Vélizy-Villacoublay, France).

Experimental tensile test of each specimen was performed with the Instron 8801 servohydraulic fatigue testing system (Instron, Norwood, MA, USA) with 3mm/min as testing speed.

4. Results and Discussion

4.1. XRCT porosity analysis

The results obtained by the XRCT porosity analysis are shown in figure 3.

According to the obtained results, Specimen 1 is free of pores, while the other specimens present different porosity distributions. Specimen 2 shows 40 pores with shape and volume close to the designed specimen.

On the other hand, Specimen 3 presents some random pores apart from the designed ones, while in Specimen 4, all the pores seem to be randomly distributed. Non programmed porosity is probably caused by manufacturing problems associated with the location of these specimens on the manufacturing plate. As stated above, these pores with irregular shapes and uncontrolled location also have their own influence on the mechanical behaviour of the specimen. Hence, a depth analysis is required.

To this end, some porosity aspects related with pore size, shape and spacing were studied. The selected characteristics are the equivalent pore diameter, the sphericity, the gap between the nearest pores and the minimum edge distance. The equivalent pore diameter indicates the diameter of the circumscribed sphere of the pore. The sphericity is defined as the ratio between the surface of a sphere with the same volume as that of the pore and the surface of the pore. Finally, the gap between the nearest pores indicates the minimum distance between the surface of the circumscribed spheres of the nearest pores, while the minimum edge distance refers to the smallest distance between the surface of the pore and the external surface of the specimen. These results are summarized in figure 4 and figure 5. Results from Specimen 1 is not presented because no defect was detected.

Figure 4 exhibits that the equivalent diameters are really close to those defined in Specimen 2. The difference between the mean equivalent diameter and the designed one is 0.087mm. The standard deviation value is 0.031mm. In contrast, the values for Specimen 3 reveal the presence of both, designed
pores and some smaller ones. Although the difference between the mean and the defined diameter decreases to 0.013mm, the standard deviation increases considerably to 0.141mm. Finally, the values for Specimen 4 seem arbitrary due to the appearance of unexpected defects. This is the cause of the growth of the difference between the mean and the defined diameter up to 0.183mm. The standard deviation also presents a high value, around 0.140mm.

Figure 4. Histograms of the equivalent pore diameter (left column) and sphericity (right column) obtained from the XRCT porosity analysis in the region of interest of each specimen.

Regarding the sphericity, figure 4 shows that Specimen 2 presents the highest ratios, followed by Specimen 3 and, finally, by Specimen 4. The mean values decrease from about 97% to 95% and 89%, respectively. In addition, the standard deviation also increases significantly, from about 0.5% to 4% and 7.6%.
According to figure 5, the gap between pores remains nearly constant in Specimen 2, as well as the minimum edge distance. Nevertheless, these values are more dispersed in Specimen 3 and Specimen 4 due to the presence of non-defined pores. These differences are noticeable in the standard deviation values, which increase from Specimen 2 to Specimen 3 and Specimen 4 in both porosity features. Regarding the gap, the values increase from about 0.030mm to 0.904mm and 1.252mm, respectively. The minimum edge distance follows the same trend, with values of 0.030mm, 0.290mm and 0.853mm.

**Figure 5.** Histograms of the gap between pores (left column) and minimum edge distance (right column) obtained from the XRCT porosity analysis in the region of interest of each specimen.

In summary, Specimen 2 presents the largest pores with spherical shape and regular distribution. Specimen 3 shows, apart from the designed pores, some nearly spherical pores, which reduce the minimum edge distance and the gap between pores, in some cases. Finally, Specimen 4 presents irregular
distribution of pores with different sizes and shapes. In addition, the minimum values of the study for both, gap and minimum edge distance are shown in this specimen.

As stated in Section 1, the failure of the component is strongly dependent on these porosity aspects due to the pore size, shape and location define the stress concentrations and lead to void growth and coalescence.

4.2. Virtual Tensile test results

In order to estimate the influence of defects on the mechanical behaviour, the XRCT data were processed and used for FEM analysis. To do it, scanned geometry was imported into ABAQUS but, previously, the tetrahedral volume meshing from polygonal mesh surfaces was performed in Matlab. For the definition of mechanical material properties in ABAQUS, the experimental data of the tensile test of Specimen 1 was used (Section 4.3) and the Poisson’s ratio was set at 0.29 according to [8]. Results of the FEM analysis are illustrated in figure 6.

![Image of Specimens](image)

**Figure 6.** Maximum principal stress on a 2D vertical section of each specimen. Results in MPa.

The analysis reveals that the stress distribution around pores depends on the loading direction. In fact, the maximum stress is located around the pore equator, and the minimum around the pore poles, when the loads of the model are applied in vertical direction. In addition, the shape of the pores would affect the stress distribution around pores. Theoretically, oblate and irregular geometries increase the stress values, while prolate shapes decrease these values. Apart from that, it is worth mentioning that the gap between pores and the minimum edge distance play a major role in the failure of the component. Reduced values of pore gaps and edge distances encourage the porosity coalescence and, thus, the earlier failure of the component.

In figure 7, the specimens present a moderately ductile fracture with cup-and-cone shape. The plane shape is commonly accomplished by the void coalescence in a plane normal to the applied load. While cone shape is due to the shear stresses. Hence, the fracture failure is strongly influenced by the stress state. According to that, the fracture starts on that plane normal to the loading direction. Therefore, the Rankine failure criteria was adopted, assuming that the increase in maximal principal stress due to the porosity aspects mentioned above, encourages the earlier failure of the component. In figure 6, Specimen 4 shows the highest values, followed by Specimen 3 and Specimen 2, respectively. Finally, Specimen 1 presents the lowest values due to the lack of defects.

Hence, the increase of stresses generated around critical pores and the reduced gaps and edge distances studied by the XRCT porosity analysis were used to estimate the failure of the component. Nonetheless, the coalescence between pores and the final fracture are not defined in this study.
4.3. Validation of the results by means of experimental tensile tests

Finally, the Engineering Stress–Strain curves, ultimate tensile strengths and elongations at fracture obtained from the tensile tests are presented in figure 7. Although all curves show similar trajectories, some specimens reach the failure earlier than others. Specimen 4 shows an elongation at fracture of 13%, whereas Specimen 3 and Specimen 2 show elongations of 16% and 26%, respectively. As depicted in figure 7, Specimen 1 is the last one that reached the failure with 30% elongation at fracture. Therefore, the results obtained by the analysis are in agreement with the experimental results.

5. Conclusions

The mechanical behaviour of Inconel 718 workpieces manufactured by L-PBF is strongly dependent on the pores generated during the manufacturing process. The pore size, shape and location, especially in terms of pore spacing and edge distance, define stress concentrations and, thus, the failure of the component driven by void growth and coalescence. Taking into account the loading direction, complex shapes, reduced distances between pores and edge distances increase the stress concentrations around pores and encourage the earlier failure of the component.

Finally, the proposed methodology is based on assessing the influence of porosity on the mechanical behaviour of the component by coupling XRCT and FEM. Although the study is in the first steps, the results obtained reveal a promising future. For future research, different data processing techniques, meshing methods and FEM modelling strategies could be studied.

Acknowledgements

Thanks are addressed to the Department of Economic Development, Sustainability and Environment of the Basque Government by funding the KK-2020/00094 (INSPECTA) research project. This work has also been supported by the InterQ project founded by European Union’s Horizon 2020 Research and Innovation programme (grant agreement No. 958357-FoF Public Private Partnership).

References

[1] Davis T, Healy D, Bubeck A and Walker R 2017 Stress concentrations around voids in three dimensions: The roots of failure Journal of Structural Geology 102 pp 193–207
[2] Timoshenko S and Goodier J N 1951 Theory of Elasticity (New York: McGraw-Hill)
[3] Pilkey W D 1997 Peterson’s Stress Concentration Factors (New York: Wiley–Interscience)
[4] Du Plessis A, Yadroitseva I, and Yadroitsev I 2020 Effects of defects on mechanical properties in metal additive manufacturing: A review focusing on X-ray tomography insights Materials
9th Manufacturing Engineering Society International Conference (MESIC 2021) IOP Publishing

IOP Conf. Series: Materials Science and Engineering 1193 (2021) 012066
doi:10.1088/1757-899X/1193/1/012066

and Design 187 p 108385

[5] Carmignato S, Dewulf W and Leach R 2018 Industrial X-Ray Computed Tomography (Springer International Publishing)

[6] Fieres J and Esposito F Accurate and efficient simulation of real pore geometries directly on CT images (https://www.tec-eurolab.com) accessed 11 January 2021

[7] Pascual A, Ortega N, Plaza S, Holgado I and Arrizubieta J I 2020 A RE methodology to achieve accurate polygon models and NURBS surfaces by applying different data processing techniques Metals 10 (11) p 1508

[8] Special Metals 207 INCONEL® Alloy 718 (Datasheet) (https://www.specialmetals.com/assets/smc/documents/inconel_alloy_718.pdf) accessed 2 March 2021