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SEM ANALYSIS OF ADDITIVELY MANUFACTURED STAINLESS STEEL 316L AND CONVENTIONAL SAMPLES

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ABSTRACT: This research paper presents for discussion a comparative investigation of Stainless Steel 316L samples fabricated by additive manufacturing (AM) and conventional production techniques, utilising Scanning Electron Microscopy (SEM). Within the study the microstructural distinctions between the two methods is examined with emphasising on grain shape and void distribution. SEM imaging is used to identify the influence of additive manufacturing on material characteristics, including the development of finer microstructures and increased residual porosity relative to traditionally produced SS316L. The findings have considerable significance for the use of SS316L in sectors necessitating exact mechanical qualities and thermal resistance.
KEYWORDS: SEM, analysis, additive manufacturing, stainless steel, 316L

1. INTRODUCTION

Stainless steel 316L (SS316L) is a commonly used material for fabricating parts in various industries, that is why this research will focus on comparing the SEM analysis results between AM and conventional fabricated SS316L with the purpose of identifying the most suitable material for using in highly radiological environments. SS316L's composition includes molybdenum that can help with corrosion resistance of this material in low enough percentages as specified by Gattu et. al. in their article [1], more specifically it enhances its resistance to pitting and crevice corrosion, making it a suitable material for harsh environments. Laser powder bed fusion facilitates the fabrication of complex geometrical components and parts with high enough precision and reduced waste and can also be useful in the production of lightweight structures and the integration of multiple components into a single part, which presents its challenges with conventional manufacturing methods. Although in the ASME code there is a 2-3% margin specified Gattu et. al. minimum percentage is 5% which would indicate that the samples used for this analysis have an optimal percentage of Molybdenum [2], [3].

It shall be noted that as per ASTM-F3184-16-2023, it is required to have a chemistry check of the final power composition to cover for variations in measurements in different laboratories [4].

Also standardised test methods are specified by ASTM with some exceptions for individual specifications of specific material [5].

The selected material, SS316L, was fabricated into several sample series and tested under similar conditions.

The comparison presented in this paper is representative for one of the series comprising of five samples of AM fabricated material and five samples of conventional material.

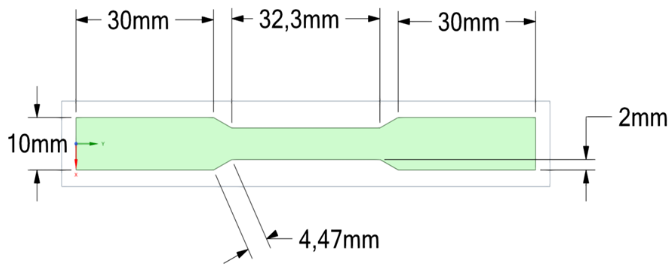

Figure 1. AM samples dimensions.

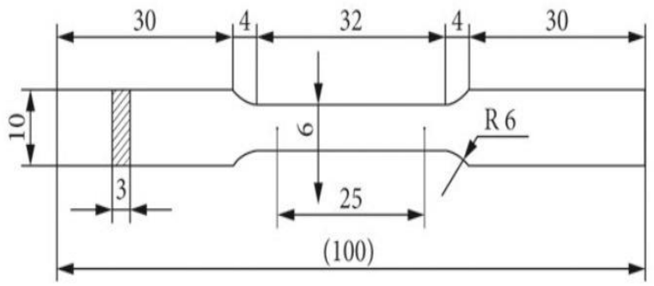

Figure 2. Conventional sample dimensions.

As specified in Figure 1 and Figure 2 the samples follow largely the same dimensions only the manufacturing methods are different, selective laser melting for AM samples and casting and forging for conventionally manufactured samples. The SEM analysis was performed after a tensile strength test was performed to observe tensile properties of samples.

In Table 1 it can be observed that both sample series follow the same material characteristics.

Based on this information, it is reasonable to state that the sample results should provide comparable results from tensile testing.

Table 1. SS316L Material composition

Cr: 16-18
Ni: 10-14
Mo: 2-3
Mn: <2
N: <0.1
Si: <0.75
P: <0.045
C: <0.03
S: <0.03

After manufacturing both sample series are visually similar as per initial dimension requirements. The sample series that are about to be analysed are presented in Figure 3 and Figure 4.

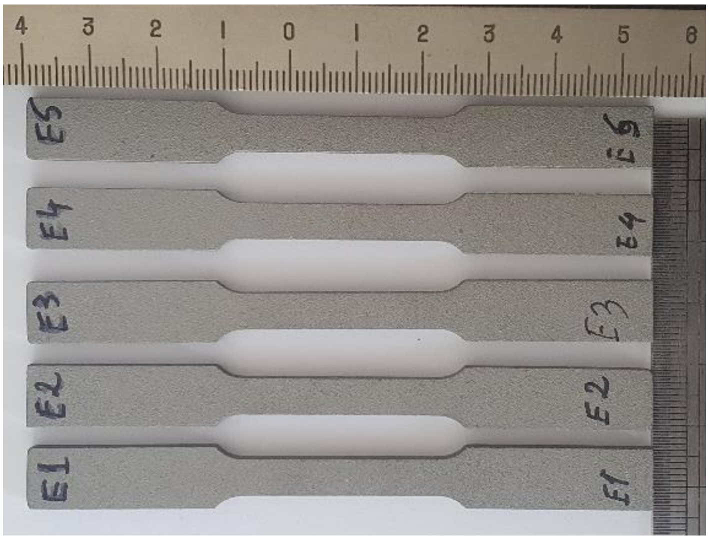

Figure 3. Manufactured AM Samples

Figure 4. Manufactured conventional Samples

Following the tensile testing, the resulting components and an intact sample were examined using SEM to see and document the observed microstructural alterations and failure mechanisms caused by mechanical deformation. The analysis was conducted at multiple magnifications to elucidate the material's behaviour under stress, the impact on grain structure, and the characteristics of fracture.

2. DATA COLLECTION AND ANALYSIS

The scanning electron microscope uses an electron gun to produce a concentrated beam of electrons, which interacts with sample atoms to produce secondary electrons, backscattered electrons, and X-rays. Multiple magnifications of this analysis aid in identifying microstructural alterations and failure processes [6], [7].

The Inspect F50 model Scanning Electron Microscope is used for high-resolution imaging of material surfaces of the samples used in this study. This model's configuration uses the electron gun, Everhart-Thornley Detector, and Backscattered Electron Detectors for secondary electron and compositional analysis and the EDAX TEAM Basic EDS system to capture X-rays for elemental analysis. The cryogenic cleaning systems called CryoCleaner ensures a clean and qualitative environment of the sample. The sample stage is motorized for control, providing detailed imaging with resolutions as fine as 1 nm into material microstructure and chemical composition [8].

Moving forward the study shall present the SEM analysis of samples.

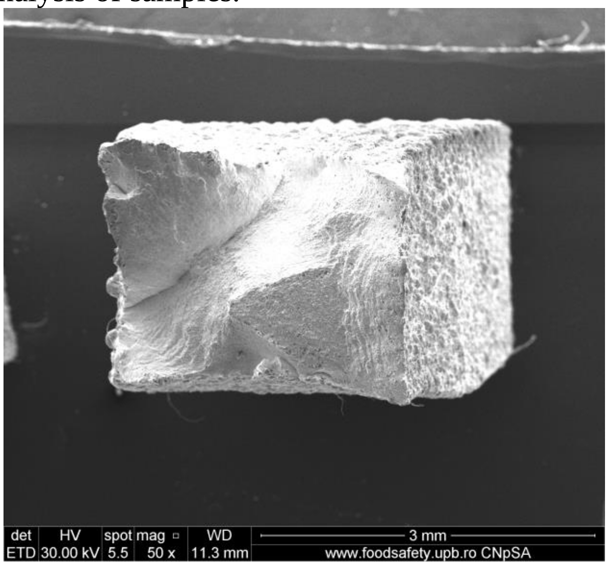

Figure 5. Surface image of AM sample

As it may be observed from Figure 5 and Figure 6 the porosity of materials is clearly visible with surfaces more porous on the AM samples compared to the conventional ones.

This research is a qualitative comparative analysis, which will continue the work presented by Sumanariu et. al. in their paper [9].

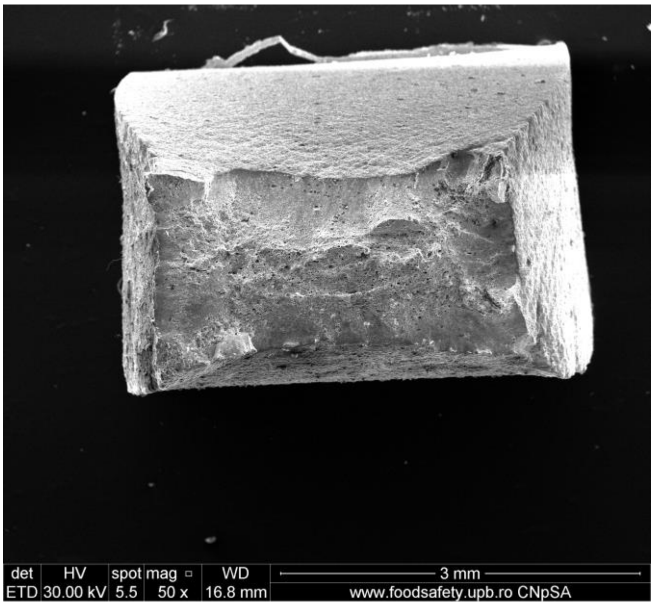

Figure 6. Surface image of conventional samples

The surfaces of the SS316L material presented in Figure 7 and qualitatively addressed in Table 2 have porous and irregular surfaces, with varying depths and pore-like structures. The upper row shows a rougher surface with depressions and ridges. The lower row shows larger cavities, due to higher magnification that highlights the microstructural features, such as grain boundaries and defects, which indicate material stress and failure points. The surface morphology is uneven and pitted due to the stresses subjected during the tensile strength tests.

SEM images in Figure 7 show that the uppermost row of voids ranges in size from 2.37 µm to 39.72 µm which indicates porosity that is not to uniform. Some voids are in the range of 3.57 µm to 22.55 µm and may be taken as small to medium-sized open pores with well-defined contours. The bottom row shows even smaller and more complex voids highlighting further that these areas have already undergone higher stresses. The features such as size and structure of voids are responsible for the properties of the material such as its strength and fatigue.

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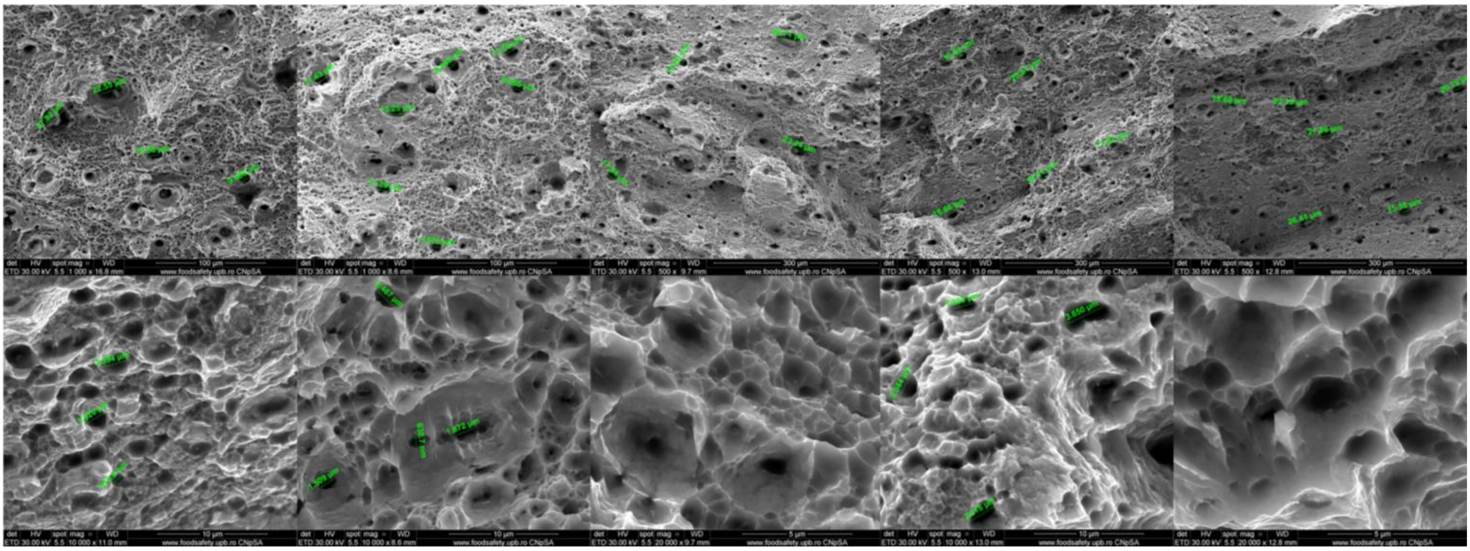

Figure 7. Conventional sample series SEM analysis [SECTION BREAK INSERTED HERE AFTER LARGE FIGURE]

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Table 2. Qualitative assessment of conventional sample series

Feature	**Description**	**Top Row**	**Bottom Row**
Pore Size	Size range of visible pores	5-10 µm	10-20 µm
Crack Width	Width of detected cracks or voids	Not Detected	1-2 µm
Surface Roughness	Qualitative assessment of surface texture	High	Moderate
Porosity (%)	Estimated percentage of the surface area occupied by pores	30%	40%
Backscattered Electrons	Brightness indicating compositional differences	Medium Contrast	Higher Contrast
Secondary Electron Contrast	Brightness or dark regions indicating surface features	High Roughness, Low Emission	Moderate Roughness, Higher Emission
Density of Defects	Number of defects such as cracks or inclusions per unit area	Low	Moderate

Phase Contrast	Differences in compositional phases detected	Visible	More Pronounced
Depressions/Ridges	Height variations on the surface indicating roughness or texture	High	Moderate

[SECTION BREAK INSERTED HERE BEFORE LARGE TABLE]

The material microstructure presented in the SEM images of Figure 8 and depicted in Table 3 can be evaluated with the help of surface properties such as the size or number of pores, the width of cracks, surface roughness and porosity. At the top row in the image, many pores and/or voids are observed, and minimal deep vein-like cracks are present having 15% to 30% porosity with high surface roughness. The bottom row of the image when taken at higher magnification shows mid-level surface roughness with more and bigger pores, more and thicker cracks, and more visible defect features. [SECTION BREAK INSERTED HERE BEFORE LARGE PICTURE]

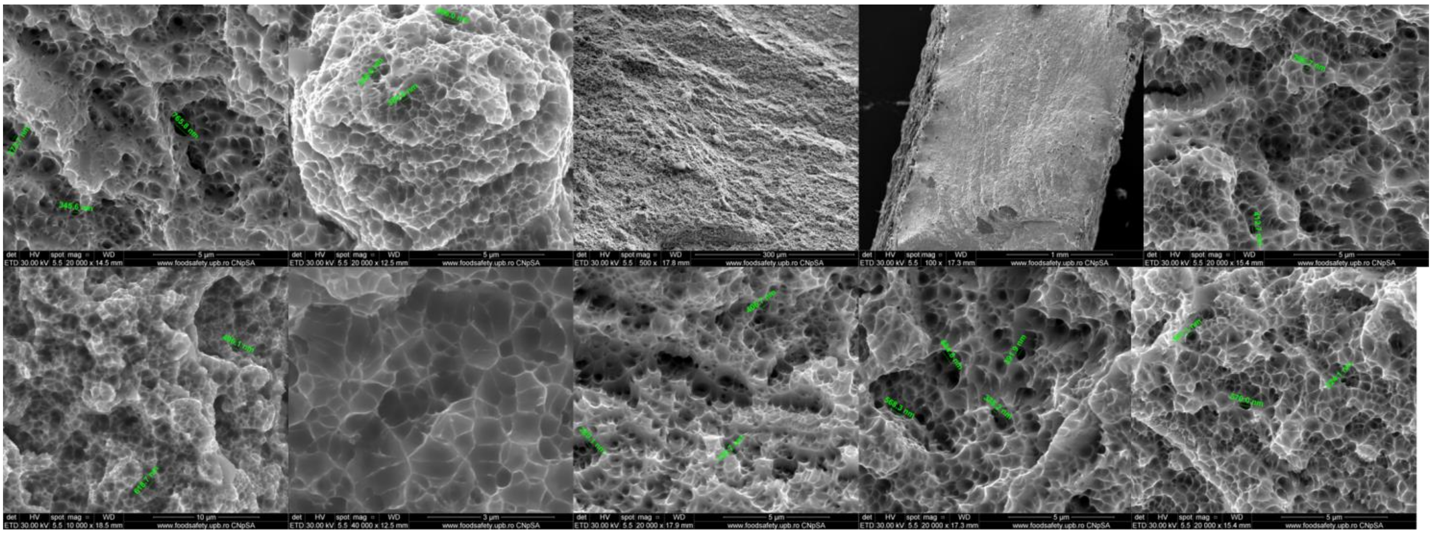

Figure 8. AM sample series SEM analysis [SECTION BREAK INSERTED HERE AFTER LARGE FIGURE]

The void sizes observed in Figure 8 for AM samples varies between 130 nm and 765 nm, indicating a small and refined microstructure. The presence of minuscule cavities indicates that the material underwent localized plastic deformation on a smaller scale, which is characteristic of materials with greater strength and microstructures composed of fine grains.

The presence of small voids, especially the 130.7 nm void, suggests that the fracture most likely started and spread through a ductile mechanism. The voids formed at a variety of small locations within the material. The presence of varying void sizes suggests that the material may have encountered different degrees of stress concentration along the fracture surface. Voids of varying sizes, ranging from 130.7 nm to 406.7 nm, demonstrate the material's ductility. These voids indicate the material's capacity to undergo plastic deformation prior to fracturing, which is a feature of ductile materials. The discovered voids likely resulted from the merging of micro voids during the material's deformation, ultimately causing it to fracture. INSERTED HERE BEFORE LARGE TABLE]

Table 3. Qualitative assessment of AM sample series

Feature	Description	Top Row	Bottom Row
Pore Size	Size range of visible pores	5-25 μm	3-30 μm
Crack Width	Width of detected cracks or voids	1-3 μm	2-4 μm
Surface Roughness	Qualitative assessment of surface texture	High	Moderate
Porosity (%)	Estimated percentage of the surface area occupied by pores	15-30%	35-40%
Backscattered Electrons	Brightness indicating compositional differences	Medium Contrast	Higher Contrast
Secondary Electron Contrast	Brightness or dark regions indicating surface features	High Roughness, Low Emission	Moderate Roughness, Higher Emission
Density of Defects	Number of defects such as cracks or inclusions per unit area	Low	Moderate

Phase Contrast	Differences in compositional phases detected	Visible	More Pronounced

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3. DISCUSSIONS AND RESULTS

The comparison of AM and conventionally manufactured SS316L samples reveals significant differences in microstructural characteristics, affecting their performance in harsh environments, particularly radiological settings. The SEM analysis reveals higher porosity and surface roughness in AM samples due to the layer-by-layer construction method, an aspect that may affect fatigue strength and long-term durability. Conventional samples show more defects and wider cracks, under lower stress compared to AM, due to rapid cooling rates and layer-by-layer deposition. The larger voids in conventional samples suggest substantial deformation under tensile stress, weakening the material's structure where as compositional contrast in AM samples is represented in the image as higher, this would mean compositional inhomogeneities due to varied cooling rates. Surface roughness in AM samples is higher, particularly in the top row of images presented, due to surface finish limitations of additive manufacturing processes, in this case only shot peening was used. This rough surface finish could lead to stress concentration points, accelerating material degradation in environments with high radiation and corrosion potential.

The main findings after the analysis are:

- AM samples exhibited significantly higher porosity compared to conventional samples;
- Voids were bigger in the conventional samples.
- AM samples has higher surface roughnes
- The density of defects, such as cracks and inclusions, was significantly higher in AM samples although presented smaller voids;
- The presence of small and large voids in AM samples indicates localized plastic deformation

4. DISCUSSIONS AND RESULTS

In conclusion, the SEM analysis reveals that while AM SS316L offers the advantage of complex geometry, reduced material waste, increased tensile strength and smaller voids post fabrication treatment is required to reduce the number of voids in the structure and surface porosity. These factors could limit the material's application in environments requiring high strength and corrosion resistance, such as radiological settings. Further optimization of the AM process, including post-processing techniques, is necessary to reduce porosity and the likelihood of defects to make AM SS316L suitable for demanding applications.

5. REFERENCES

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