Microscopic and mesoscopic/ macroscopic structural characteristics of material extrusion Steel 316L: influence of the fabrication process

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Abstract
Purpose – The material extrusion (ME) process induces variations in the final part’s microscopic and macroscopic structural characteristics. This viewpoint article aims to uncover the relation between ME fabrication parameters and the microstructural and mesostructural characteristics of the ME BASF Ultrafuse Steel 316L metal parts. These characteristics can affect the structural integrity of the produced parts and components used in various engineering applications.

Design/methodology/approach – Recent studies on the ME BASF Ultrafuse Steel 316L are reviewed, with a focus on those which report microstructural and mesostructural characteristics that may affect structural integrity.

Findings – A relationship between ME fabrication parameters and subsequent microstructural and mesostructural characteristics is discussed. Common microstructural and mesostructural/macrostructural defects are also highlighted and discussed.

Originality/value – This viewpoint article attempts to bridge the existing gap in the literature, highlighting the influence of ME fabrication parameters on Steel 316L parts fabricated via this additive manufacturing method. Moreover, this article identifies and discusses important considerations for the purposes of selecting and optimising the structural integrity of ME-fabricated Steel 316L parts.

Keywords Material extrusion, Steel, Microstructure, Macroscopic characteristics, Manufacturing parameters

Paper type Technical paper

1. Introduction
The material extrusion (ME) process, also known as the fused filament fabrication (FFF) or fused deposition modelling process (FDM), was first patented in the late 1980s by Stratasys Ltd as the FDM process (Turner et al., 2014; Vafadar et al., 2021). However, over time, as this fabrication method continued to gain acceptance and popularity in the additive
manufacturing (AM) community, the initial Stratasys patents expired in the late 2000s, leading to the introduction of the FFF-type open-source systems (Turner et al., 2014; Vafadar et al., 2021). Open-source printers enable the production of parts/components with materials from different suppliers. The ME or the FFF process was originally designed and marketed to produce polymer-based parts/components (Turner et al., 2014). However, further advancements in AM subsequently led to the introduction of metal-polymer filaments (such as BASF Ultrafuse Steel 316L), which can be printed on any open-source printer.

In the ME fabrication process, the molten or melted filament is extruded via the printing nozzle and deposited on a heated printing bed to facilitate adhesion between the bed and the part being printed (Vafadar et al., 2021; Varotsis and Simon, 2022). The material is continuously extruded and deposited layer-by-layer until the part is completed (according to the computer-aided design file). In addition, it is noteworthy to mention that the overall quality, mechanical properties and, in effect, structural integrity of the ME part depend on the optimisation of the production conditions, depending on the material and design requirements (Turner et al., 2014). Furthermore, as with other AM methods, there are challenges associated with the production of parts via the ME process. Varotsis and Simon (Varotsis and Simon, 2022) highlight three main challenges including:

1. **Warping** is one of the most common limitations in the ME fabrication process. Following the extrusion of a layer, its dimensions decrease as it solidifies. However, subsequent extruded layers cool at different rates, leading to thermal gradients and then warping of the parts, as depicted in Figure 1(a). Varotsis and Simon (Varotsis and Simon, 2022), amongst others, suggest monitoring the print bed temperature and increasing the adhesion between the print bed and part to reduce warping.

2. **First layer adhesion** is the most critical layer in the print’s success because it forms the foundation of the part, and subsequent layers press against it. And the lack of layer bonding will eventually lead to warping of layers and distortion of the part. Turner et al. (2014) recommend printing in an enclosed chamber or temperature-controlled oven to combat layer adhesion issues, while Cain (2022) recommends applying adhesive to the print bed.

3. **Generating support structures** is another limitation of the ME process (Cain, 2022). Of course, printing support structures will require additional material as depicted in

![Figure 1. Schematic representation of common ME fabrication process challenges: (a) warping defect in ME process (Varotsis and Simon, 2022); (b) parts printed with support structures during the ME process (Cain, 2022)](image-url)
Figure 1(b), incurring additional costs (Cain, 2022). Depending on the design, support structures may be required, resulting in additional post-processing to improve the overall quality of the part. Varotsis and Simon (Varotsis and Simon, 2022) recommend designing parts/components that require less or no support structures.

Overall, the ME process mirrors the standard AM metal fabrication process to produce the “green” parts. However, these parts require further debinding and sintering process to remove the polymer binder and obtain the final metal part. This viewpoint article focuses on the influence of ME fabrication parameters on subsequent microstructural and mesostructural characteristics of the ME Ultrafuse Steel 316L parts, with more focus on the latter due to the more available literature. These characteristics are expected to affect the structural integrity of the produced parts and components used in various engineering applications.

2. Influence of process parameters

2.1 Influence on microstructure

Gong et al. (2019) noted that the grain size of ME Steel 316L depends on “the duration and temperature of sintering”. Sintered as-built Ultrafuse Steel 316L microstructures have been reported to (generally) exhibit equiaxial coarse grains, albeit with some variations in grain size and apparent porosity. Damon et al. (2019) measured an average grain size of 25 µm, Jiang and Ning (2021), Sadaf et al. (2021), and Santamaria et al. (2022) reported an average grain size ranging from 40 µm to 45 µm. On the other hand, Rane et al. (2018) and Caminero et al. (2021, 2022) noted that their respective sintered parts’ microstructures exhibited grain sizes ranging from 57 µm to 103 µm.

Furthermore, Wang et al. (2021) observed the coexistence of ferrite and austenite phases, with the ferrite phase observed near the grain boundaries of the austenite phase. They attributed their coexistence to the high-temperature sintering requirements of the green part. Jiang and Ning (2021) observed pore distribution on the grain boundaries, although without varying printing parameters. Interestingly, Caminero et al. (2022) attributed the pore distribution in the microstructure of ME Steel parts to the influence of layer height, deposition strategy and line width (a function of nozzle diameter). Tosto et al. (2021) and Liu et al. (2020) established that the voids observed in the microstructure of the sintered metal parts stem from the ME production process, resulting in poor interlayer bonding in the sintered parts. Santamaria et al. (2022) and Damon et al. (2019) similarly observed voids of various sizes, corroborating the findings of the aforementioned authors; they noted that the porosity content of the sintered part depends on production parameters employed, including varying raster angle and build orientation. Meanwhile, Tosto et al. (2022) found that an increase in layer height (from 0.09 mm to 0.14 mm) and flow rate (from 100% to 110%) improves the microstructural grain size of ME Steel 316L parts. The authors found specimens produced with higher layer height (0.14 mm) and flow rate (110%) to exhibit “a lower average grain area and narrower distribution” of microstructural grains. Overall, they attributed the reduced discontinuities within the raster layers to “the higher amount of metal powder in the green sample” compared to their counterparts produced with lower print parameters.

Inclusions have been identified as another common shortcoming of the ME process for Steel 316L parts production, which can also be detrimental to the structural integrity of ME parts/components. Inclusions can stem from the varying debinding and sintering processing conditions due to the high-temperature requirements and the varying post-processing environment. Tosto et al. (2021) noted that the interaction of the polymer binder with the Steel 316L powder during the sintering process could facilitate (unwanted) particle inclusions. The authors observed higher carbon concentrations on the raster surface, concluding that it
emanated from the polymer binder. Santamaria et al. (2022) observed chromium (Cr) and silicon (Si) particle inclusions sizes ranging from 1.4 μm to 3 μm in the sintered Steel 316L parts. Examples of typical ME Steel 316L microstructures as reported in the literature are shown in Figure 2.

2.2 Influence on mesostructure/macrostructure
Inherent fabrication-induced defects have continued to impede the further application of the BASF Ultrafuse Steel 316L parts/components for safety-critical structural applications. As with other metal AM methods, the most common production process-induced defect identified in the literature is porosity. Porosity can be the source of crack initiation and quick degradation of a part’s structural integrity. As previously discussed in section 2.1, porosity stems from the ME production process, resulting in voids and poor interlayer bonding (Tosto et al., 2021) within the raster layers at the mesostructural/macrostructural level. Tosto et al. (2022), who varied nozzle temperatures (240 and 250°C), layer heights (0.09 mm and 0.14 mm) and flow rate (100% and 110%) established that a decrease in nozzle temperature during ME fabrication increases air gaps in the green part, negatively affecting interlayer bonding between the rasters, which effectively induces residual stresses in the specimens. On the other hand, specimens produced with a higher flow rate (110%) and layer height (0.14 mm) were found to exhibit reduced discontinuities within the raster layers. Tosto et al. (2021) attributed the pores between rasters to incomplete fusion of the raster layers. Damon et al. (2019) added that inadequate extrusion at the contact points further exacerbates poor interlayer bonding if the material extrusion is insufficient. Wang et al. (2021) attributed the anisotropic mechanical performance of their ME Steel 316L samples to the pore chains they observed in the interlayer region of the samples. In a similar vein, Santamaria et al. (2022) attributed the presence of elongated macro-porosity in their ME Steel 316L samples to the “inherent nature of the line-by-line and layer-by-layer process, regardless of feedstock or post-processing”.

2.3 Process optimisation: reducing process induced defects
The aforementioned defects must be adequately controlled to reduce mechanical anisotropy and improve the mechanical performance of ME Ultrafuse Steel 316L samples/parts/components. Tosto et al. (2021) recommended further research into optimising ME print settings to reduce fabrication-induced defects. In line with this, Gong et al. (2019) recommended the print speed of 60 mm/s, layer height of 0.2 mm and nozzle temperature of 235°C to reduce interlayer

Figure 2.
Typical microscopic images of sintered ME Steel 316L microstructure as reported in the literature:
(a) coexistence of ferrite and austenite phases (Wang et al., 2021);
(b) slight variation in grain size and presence of twin interfaces (Liu et al., 2020)

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delamination and voids in the green and sintered parts. Kurose et al. (2020) found that voids can be reduced by controlling the print layer height. Jiang and Ning (Jiang and Ning, 2021) recommended increasing the sintering temperature and varying the sintering environment to reduce porosity. On the other hand, Caminero et al. (2021) argue that these measures will not fully eliminate fabrication-induced porosity. Hence, Wang et al. (2021) proposed the hot isostatic pressing process to reduce porosity and eliminate anisotropic mechanical behaviour. Reducing the anisotropic behaviour of ME metal parts (especially when less likely to be predicted by models) is a characteristic the designer would need to control to produce structurally reliable AM parts, components and structures. Additionally, depending on the design requirements, reducing the thermal gradient to the barest minimum during part fabrication will further facilitate interlayer bonding, subsequently reducing interlayer gaps. Examples of typical microstructure and mesostructure defects of ME Steel 316L defects as reported in the literature are shown in Figures 2 and 3.

Figure 3.
Typical microscopic images of the mesostructure of ME Steel 316L green and sintered parts: (a) fabrication-induced voids/pores (Tosto et al., 2021); (b) fabrication-induced print gaps (Liu et al., 2020) (c) horizontal pore chains of various sizes (Wang et al., 2021)

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3. Discussions and conclusions

The influence of fabrication parameters on the ME Steel 316L parts’ microscopic and mesoscopic/macroscopic characteristics has been evaluated from the published literature towards building an understanding of their possible effect on structural integrity. Although fairly equiaxed microstructure grains have been reported in the literature, the ME metal parts have also been observed to exhibit heterogeneous grain structures. To corroborate this, Rane et al. (2018) and Santamaria et al. (2022) measured structures of various grain sizes following scanning electron microscopy analysis. The variation in (microstructure) grain sizes reported in the above studies further confirms that the microstructure of ME metal parts is effectively unique to the type of machine, the quality of the base material and the production process employed. Regarding mesostructural/macrostructural characteristics of Steel 316L, it is evident from the literature that production-induced defects induce voids and porosities in the parts. Production issues, including incomplete fusion of raster layers and inadequate extrusion at the contact points, are the commonly reported issues affecting structural integrity, which subsequently induces mechanical anisotropy.

Overall, this suggests that besides the ME print process parameters employed, the debinding and sintering process also affect microstructural and mesostructural/macrostructural characteristics, which ultimately jeopardises the structural integrity and the detectability of defects in ME Steel 316L parts (Jiang and Ning, 2021; Obadimu et al., 2021). Furthermore, it has also been noted that the porous nature of the sintered microstructures facilitates anisotropic mechanical behaviour owing to the variation in grain sizes (Rosnitschek et al., 2021). Kasha et al. (2022) who observed variations in flexural strength values, similarly confirmed the influence of varying ME production processes.

The key conclusions to draw from this technical paper are:

(1) The microstructural and mesostructural/macrostructural characteristics of ME Steel 316L parts depend on the production process. As detailed in the paper, variations manufacturing parameters (such as layer height, raster angle, and nozzle temperature) and the debinding and sintering processing conditions (such as varying processing temperatures) have been reported to induce variations in the structural characteristics.

(2) Researchers need to control appropriately the ME AM (printing) fabrication process to minimise their subsequent impact on structural integrity. Hence, optimising fabrication parameters (i.e. the optimum combination of manufacturing parameters) will reduce variations in ME Steel 316L microstructure (grain size), reducing fabrication-induced porosity. However, Tosto et al. (2021) recommend further research in this regard to achieve this.

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