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## **VOID REDUCTION STRATEGIES IN MATERIAL EXTRUSION ADDITIVE MANUFACTURING OF METAL PARTS: A REVIEW**

**Felipe Gonçalves Di Nisio**

**Neri Volpato**

Federal University of Technology - Paraná (UTFPR), Department of Mechanical Engineering, Curitiba-PR, Brazil  
felipenisio@alunos.utfpr.edu.br, nvolpato@utfpr.edu.br

**Abstract.** *Material extrusion (MEX) is one of the most widely used Additive Manufacturing (AM) technologies due to its simplicity and possibility to use low-cost equipment. Recently, it has gained interest in the production of metal parts, where a combination of metal powder and a polymeric matrix is used as feedstock to produce a green part. The green part is then submitted to a debinding process, where the polymer is eliminated from the structure, and then to a sintering process, resulting in a 100% metallic part. Metallic parts obtained this way present undesirable internal voids due to inherent characteristics of the MEX process, even when 100% infill density is used. Developing strategies to reduce void formation is desirable in the metal MEX process since they compromise the mechanical performance of the final part. This review paper investigates void reduction strategies used for metal MEX. The results show that the geometry of deposited filaments is one of the main mechanisms of void formation, and several aspects can influence its dimensions and distributions, such as part geometry, layer height, extrusion width, and tool-path planning. In general, printing speed, extrusion rate, and nozzle temperature are key parameters in this process. This study contributes to the development of metal MEX, as it summarizes the strategies to obtain less porous parts with better mechanical properties. Still, there is room for new developments since only a few studies focused on void reduction in metal parts obtained by MEX.*

**Keywords:** *Additive Manufacturing, Material Extrusion, Porosity, Process Planning, Mechanical Properties*

### **1. INTRODUCTION**

In recent years, Additive Manufacturing (AM) has garnered more attention as a fabrication process mainly due to its unique ability to produce parts with geometric freedom that cannot be achieved through traditional subtractive manufacturing. Material extrusion (MEX) is one of the most commonly used AM technologies due to its low-cost equipment, simplicity, and versatility with materials (Sun *et al.*, 2023; Suwanpreecha and Manonukul, 2022).

Recently, a new application of this technology has emerged, specifically to produce metal parts. Known as metal MEX, this process involves printing the desired geometry using a polymer-metal composite as feedstock, similar to the Metal Injection Molding (MIM) method. The printed structure is then subjected to post-processing steps to create the final metallic part. The first step, called debinding, removes most of the polymeric components of the structure. Next is the sintering process, which results in a 100% metal part, causing a 15-20% shrinkage in the volume (Quarto *et al.*, 2021; Rosnitschek *et al.*, 2021; Thompson *et al.*, 2019; Caminero *et al.*, 2021; Galati and Minetola, 2019).

While metal MEX allows for the easy and cost-effective fabrication of metal parts at first glance, compared to other AM technologies, such as Powder Bed Fusion (PBF), also referred to as Selective Laser Melting (SLM), the resulting mechanical properties are typically lower (Gong *et al.*, 2019). The reason is that the metallic parts produced by metal MEX tend to have inherent porosity after the sintering process (Caminero *et al.*, 2021; Damon *et al.*, 2019). Most of this porosity results from the formation of internal voids during the MEX printing process, which is affected by several printing parameters. The reduction or even elimination of the voids is necessary to increase the mechanical properties that can be obtained with metal MEX.

Looking to contribute to the development of metal MEX applications, this work presents a literature review of void reduction strategies for this fabrication process. Some strategies used for void reduction in polymer MEX are also analyzed, and their application on metallic parts is discussed. The work is structured as follows: first, a review of void types and their formation mechanism is carried out in Section 2. In Section 3, the main void reduction strategies found in recent articles are presented. Lastly, Section 4 summarizes the conclusions of the study.

### **2. TYPES OF VOIDS IN MEX**

Before analyzing void reduction strategies, it is important to understand the mechanisms that generate the internal voids and what process parameters can influence them. Basically, the several voids encountered on the MEX printed parts can be divided into three main categories: layer voids, inter-filament voids, and material porosity.

## 2.1 Layer voids

This type of void occurs during the deposition of filaments to print a single layer. These voids can be observed in the XY plane of the printed parts, as shown in the example of Fig. 1a. They usually are a result of the curved corners in the toolpath when turning the direction of the extruder nozzle during printing, as shown in Fig. 1b (Tao *et al.*, 2021). These voids also appear when an area that needs to be filled is not an exact multiplier of the filament extrusion width (Fig. 1c).

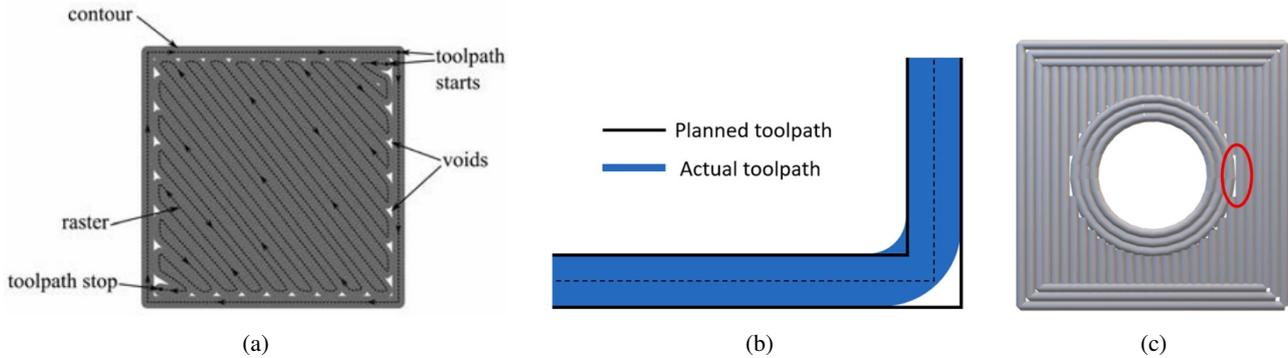


Figure 1: Representation of voids formed in a layer (XY plane) (Turner and Gold, 2015) (a), difference between planned and actual toolpath in MEX (Sun *et al.*, 2023) (b) and infill area smaller than extrusion width (Sun *et al.*, 2023) (c).

The formation of layer voids is highly dependent on the toolpath/trajectory of the extruder nozzle (filling pattern). MEX's most common filling strategies are raster (also known as zigzag or rectilinear) and concentric (or contour). In raster filling, several printing parameters can be varied to control the formation of voids in the layer. One of them is the gap, which defines the distance between two adjacent filaments. A positive gap value is used when voids are desirable (to reduce a part's weight, for example), but when the infill density is set to 100%, the gap value is usually 0, causing the adhesion of adjacent filaments. A negative gap value can also be set in the process planning causing an overlap between deposited filaments.

The raster angle parameter determines the orientation of the deposited filaments on a layer in a raster filling pattern. Depending on the part's geometry, this parameter can also influence the dimensions and positions of voids formed on the layer. Figure 2 shows an example of a raster angle variation in a triangular-shaped layer. A common technique used with raster filling is the rotation of raster angles between layers (usually  $90^\circ$ ), which can be helpful to avoid the formation of voids of different layers in the same position.

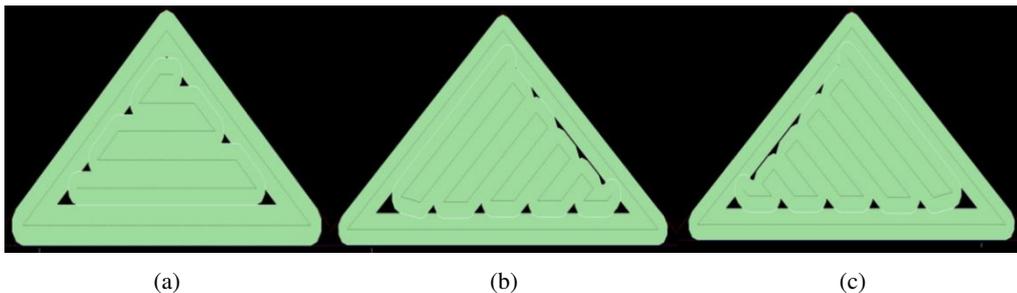


Figure 2: Void formation on a layer using  $0^\circ$  (a),  $37^\circ$  (b) and  $53^\circ$  (c) raster angle (Eiliat and Urbanic, 2017).

The extrusion width parameter defines the width of the deposited filaments. Lower extrusion widths can result in a smaller void area on the layer, as shown in Fig. 3. Although this parameter can be lowered to reduce void sizes it increases the printing time (Qiu and Langrana, 2002).

## 2.2 Inter-filament voids

In MEX printing processes, the cross-section of deposited filaments usually presents an elliptical shape. During deposition, adjacent filaments are partially bound while the melted material lowers its temperature. Because of this, inter-filament voids are formed when two or more layers of filaments are stacked (Fig. 4). These voids can be observed in an XZ or YZ plane, being Z the building direction. Several printing parameters can influence the formation of inter-filament voids, such as extruder temperature, extrusion multiplier, layer height, and printing speed.

The extrusion temperature is an essential parameter in MEX that can influence several properties of a printed part. Each type of material has a temperature range in which it can be processed. Higher temperatures can lower the melt viscosity and improve filament adhesion, but it also decreases the dimensional accuracy of the printed part.

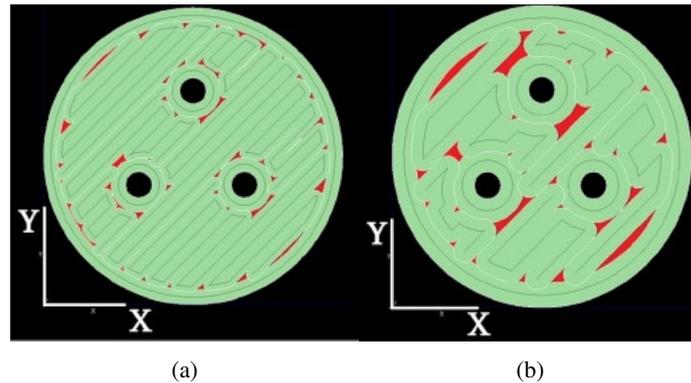


Figure 3: Different void area sizes in a layer with smaller (a) and higher (b) extrusion width values. Voids are highlighted in red (Eiliat and Urbanic, 2019).

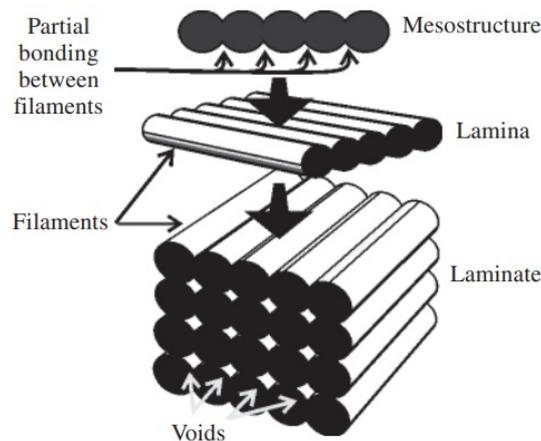


Figure 4: Formation of inter-filament voids when stacking layers (lamina) (Bellehumeur *et al.*, 2004).

Layer height (or layer thickness) is a parameter that directly impacts a printed part's quality and building time. Thinner layers can reduce the size of inter-filament voids but also increase the number of voids formed since more layers will be necessary to build the printed part (Tao *et al.*, 2021).

The extrusion multiplier (also called extrusion rate or flow rate) parameter determines the amount of material fed through the extruder nozzle. It is usually indicated in a percentile value, where 100% represents the material required to deposit filaments with the designated dimensions (extrusion width and layer height). When this parameter is increased, more material is deposited during the printing process, and the excess material can fill the spaces between filaments, reducing the size of inter-filament voids (Gordeev *et al.*, 2018).

The printing speed parameter can also influence the size of the voids in a MEX printed part. According to Tao *et al.* (2021), lower printing speeds allow longer heat transfer times during deposition, resulting in better coalescence between the filaments and minimizing void sizes. This relation is shown in the work of Abbot *et al.* (2018), where parts printed with 50 mm/s presented larger voids than the ones printed with 10 mm/s.

### 2.3 Material porosity

Material porosity occurs at a smaller scale than the other types of voids previously discussed. It is defined by pores located in the interior of the deposited material. This void type is more common in MEX processes with composite materials, such as filaments with carbon fiber, glass fiber, or metallic/ceramic powder. In the case of metal MEX, these pores are expected to be present in the final metallic part obtained after the sintering process. The post-processing parameters (sintering temperature and time) have a direct influence on the formation of material porosity (Suwanpreecha and Manonukul, 2022; Damon *et al.*, 2019).

The size of the metallic powder grains can also impact the material porosity of sintered parts. According to Singh *et al.* (2021a), using finer powders results in less porosity when compared to large powders. However, it also causes more shrinkage after sintering.

### 3. VOID REDUCTION STRATEGIES

#### 3.1 Printing parameters

According to Akhouni and Behraves (2019), the concentric filling has fewer voids in the layer than the other strategies used in MEX. However, this can vary greatly depending on the geometry of the part. In the literature, most Metal MEX studies use raster filling. According to Suwanpreecha and Manonukul (2022), metal parts manufactured with 100% filling have similar properties even with different filling patterns.

One of the most common methods to reduce layer voids is to apply a negative gap value in the filling strategy, generating an overlap between deposited filaments (Eiliat and Urbanic, 2017). The overlap can also be applied between the layer's contour and filling, reducing the voids formed due to the toolpath's direction turning. However, if the overlap value is too high, deformations may occur in the part during printing, compromising its dimensional accuracy (Gibson *et al.*, 2015).

Several studies investigated the influence of the raster angle parameter on the mechanical properties of printed parts, but only a few related the results with void formation/porosity. Xu *et al.* (2023), in their study, obtained higher density parts when using a rotation of raster angle between layers compared to layers printed in the same direction. According to the authors, eliminating redundant trajectories between two layers makes the deposited material in the upper layer fill inter-filament voids in the bottom layer.

In order to reduce layer voids in MEX parts, Qiu and Langrana (2002) proposed a filling method that uses an adaptive extrusion width, which reduces this parameter only in specific regions to reduce voids sizes, as shown in Fig. 5. The authors also used the lower extrusion widths to fill voids that would be formed with a fixed width. Notably, layer voids were almost eliminated with this method. Following a similar purpose but for a concentric filling pattern, Jin *et al.* (2017) proposed a filling optimization strategy that uses variable extrusion widths to fill layer voids that would be formed with a fixed width. An example of this optimization is shown in Fig. 6

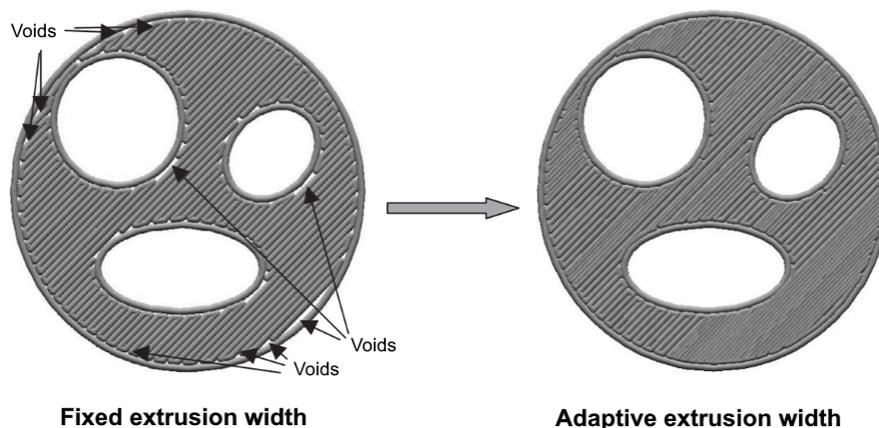


Figure 5: Reduction of layer voids by using an adaptive extrusion width (Adapted from Qiu and Langrana (2002)).

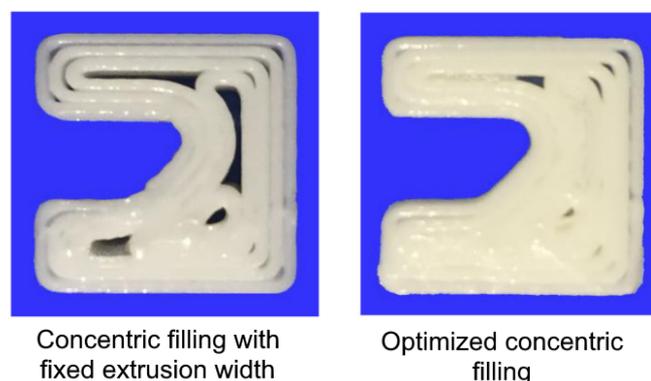


Figure 6: Result of an optimized concentric filling using variable extrusion width (Adapted from Jin *et al.* (2017)).

Studies showed that higher extrusion temperatures are capable of reducing the size of inter-filament voids since it promotes a better coalescence between deposited filaments (Wang *et al.*, 2019; Wolszczak *et al.*, 2018; Godec *et al.*, 2020). In metal MEX, these temperatures range between 80 and 260 °C, depending on the polymer used as a matrix for

the metal powder (Suwanpreecha and Manonukul, 2022). This parameter should be set to the highest possible to minimize void formation. However, temperatures that are too high can generate residual stress, leading to warpage and deformation of printed parts (Singh *et al.*, 2021b).

Several authors report that the reduction of layer height results in more resistant metal parts due to inter-filament void reduction (Quarto *et al.*, 2021; Singh *et al.*, 2021b; Hassan *et al.*, 2021), but also increases printing time. The layer height values used in the literature vary from 0.05 to 0.4 mm and depend mainly on the resolution of the equipment used (Suwanpreecha and Manonukul, 2022).

Higher extrusion rates can also reduce the size of inter-filament voids. As this parameter increases, more material will be deposited during printing, filling empty spaces and increasing the part's mechanical strength (Godec *et al.*, 2020). In the works of Thompson *et al.* (2019) and Safka *et al.* (2020), a slight increase in the extrusion rate (5-6%) was applied to produce metallic parts with higher density. In a study focused on reducing voids in polymer parts, Ghorbani *et al.* (2022) were able to eliminate inter-filament voids between layers by applying an extrusion rate of 120%, as shown in Fig. 7. In addition, the authors comment that for higher extrusion rate values, it is necessary to work with higher temperatures of the extruder nozzle. According to Gonzalez-Gutierrez *et al.* (2018), extrusion multipliers between 150 and 200% can reduce void sizes in metal MEX. However, Rosnitschek *et al.* (2021) reported that an excessive extrusion rate (close to 200%) results in deformations in the printed part.

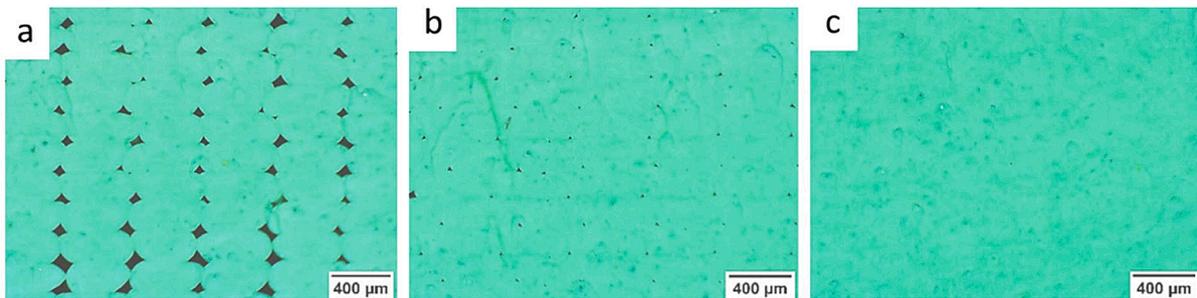


Figure 7: Cross-sections of polymeric parts printed with 100% (a), 110% (b) and 120% (c) extrusion multiplier (Ghorbani *et al.*, 2022).

As discussed in Section 2.2, the printing speed parameter can also influence the dimensions of inter-filament voids in the printed part. Since the addition of metallic components in the feedstock increases the viscosity of the material, printing speeds used in Metal MEX are lower when compared to the speeds for polymeric MEX (Shaikh *et al.*, 2021). Typical values of this parameter usually vary between 15 and 30 mm/s for printing metallic parts (Safka *et al.*, 2020; Caminero *et al.*, 2021). According to Singh *et al.* (2021b), printing speeds between 5 and 15 mm/s tend to result in denser parts but with a longer printing time.

Although many authors were concerned about reducing voids in parts obtained in MEX, most studies applied a single parameter's variation to investigate its relation with void sizes/quantity. Combining two or more void reduction strategies may be used to achieve better results. All printing parameters must be optimized to reach a lower porosity without compromising the dimensional accuracy or deforming the printed parts. A frequent combination of low printing speeds, high extrusion temperatures, and a slight increase in extrusion multiplier is notable in the literature for void reduction in the metal MEX process.

### 3.2 Post-processing parameters

After the green part is printed in the metal MEX process, it is submitted to a debinding process, where most of the polymeric components of the part are eliminated. In the literature, there is no mention of the influence of debinding parameters in void formation. However, in the next post-processing step (sintering), the parameters chosen are crucial to improving the final part's density (Damon *et al.*, 2019).

Higher sintering temperatures and longer sintering times can be used to achieve sintered parts with less material porosity. Nonetheless, it is essential to highlight that too high sintering temperatures and times can cause significant grain growth, which reduces mechanical properties. For two of the most common materials in metal MEX, 316L and 17-4PH stainless steels, sintering temperatures usually range between 1100 and 1380 °C, while sintering times vary between 1 and 4 hours (Suwanpreecha and Manonukul, 2022). Figure 8 shows the reduction of material porosity achieved when optimizing sintering parameters in 316L samples obtained by metal MEX.

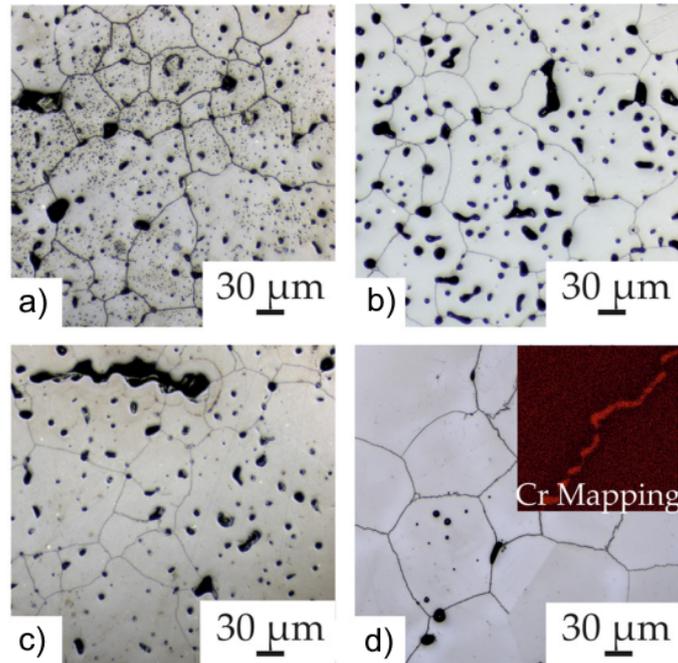


Figure 8: Microstructures of 316L samples after sintering for 120 min at 1340 °C (a), 1350 °C (b), 1360 °C (c) and 1360 °C with a lower heating rate (d) (Thompson *et al.*, 2019).

#### 4. CONCLUSIONS

The metal MEX process brings a new perspective to the fabrication of metal parts with AM, exploring geometric complexities in a method that can be more cost-effective than other technologies, such as PBF/SLM. However, there is still room for improvement regarding the mechanical properties of the printed parts. Because of this, many authors explored methods to reduce the size and amount of voids formed on the parts' interior during the fabrication process.

A combination of several printing and sintering parameters needs to be optimized to achieve parts with high density in metal MEX. Studies report sintered parts with densities varying between 91,1% and 99,5%, being the highest value obtained with an optimal combination of process parameters. It is also important to emphasize that these parameters depend on the material and the equipment used. For that reason, the definition of which void reduction strategy (or strategies) is suited for a determined application will depend on several tests/experiments to be conducted to determine the parameter values that result in the lower porosity.

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