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Manufacturing strategy for additive manufacturing of a piping component for oil and gas application

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Abstract. Additive manufacturing, or 3D printing, has been the most developing, desired manufacturing process in the manufacturing industry for the last three decades. Ease of application, design of freedom, and variety of materials application attracted all industries manufacturers to shift their dependency of the traditional manufacturing processes to acquire an innovative state-of-the-art solution at the most affordable cost. AM manufacturing provides parts with the optimum processing factors and the least material wastage. Strength and final dimensional accuracy are vital in AM parts creation. This paper will demonstrate the DfAM to fabricate a piping spacer for the oil and gas piping system. Also, it will shed light on the main elements that impact DfAM's strategy. All related manufacturing parameters: including infill, printing orientation, and material selection analyzed, to acquire a robust part created using the FDM process to ensure the final product is safely utilized for the oil and gas industry application.

Introduction

Additive manufacturing is an evolving state-of-the-art fabrication process wherein all industries seek to adopt as an alternative to traditional fabrication processes. 3DP or additive manufacturing (AM) is a process driven by manufacturing using three-dimensional model data and building the materials to develop the final product. This fabrication process can produce parts with various complex geometries and design freedom from constraints. Initially, 3DP was only used for prototyping purposes. In recent years the convergence of 3DP from prototyping to products was increased due to ease of creation and diverse final product sizes with affordable cost regardless of the product quantities. AM is one of the leading enablers transforming the manufacturing industries to a new perspective of sustainability and recyclability. AM has become an attractive market for manufacturers, leading to tremendous acceleration in the development of AM methodologies. The predicted global economic growth for 3DP was estimated to approach USD 23.33 billion by 2026 [1]. AM is generated from a physical model that relies on a computer-aided design (CAD) model. The AM starts by transforming the CAD model format into a Standard Tessellation Language (STL) type file, entailing the part geometry and layout. Then, the STL files are sliced into the 2D cross-sectional layers with nearly 0.01–0.7 mm of thickness for the component and printed using one of AM methodologies [2]. The overall AM essential manufacturing steps are illustrated in Fig 1. All AM methods use the same processing steps until the construction of all layers one above each other, which is finally completed by post-processing or curing as required [3]. ISO/ASTM 52900 classified AM processes into the following categories: material extrusion, powder bed fusion, vat polymerization, directed energy deposition, material jetting, binder jetting, and sheet lamination [3].

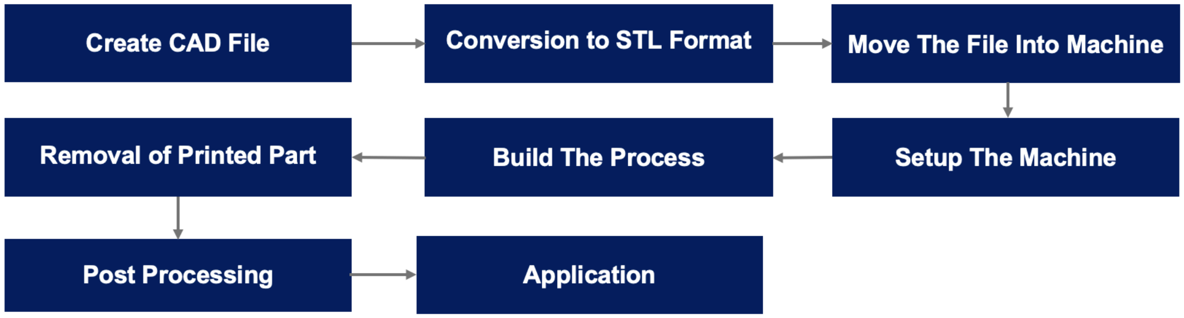

Fig 1 AM Overall essential Manufacturing Steps

Process Flowchart

AM part creation process for oil and gas applications starts with the potential component selection by evaluating: needs, risk, and experience for fabrication. The main target is to assess the overall feasibility of part fabrication to move to the next step. DFAM framework is the second step that is developed based on the performance specification of the part. This step is crucial since the component material and design are created, guiding the AM process selection.

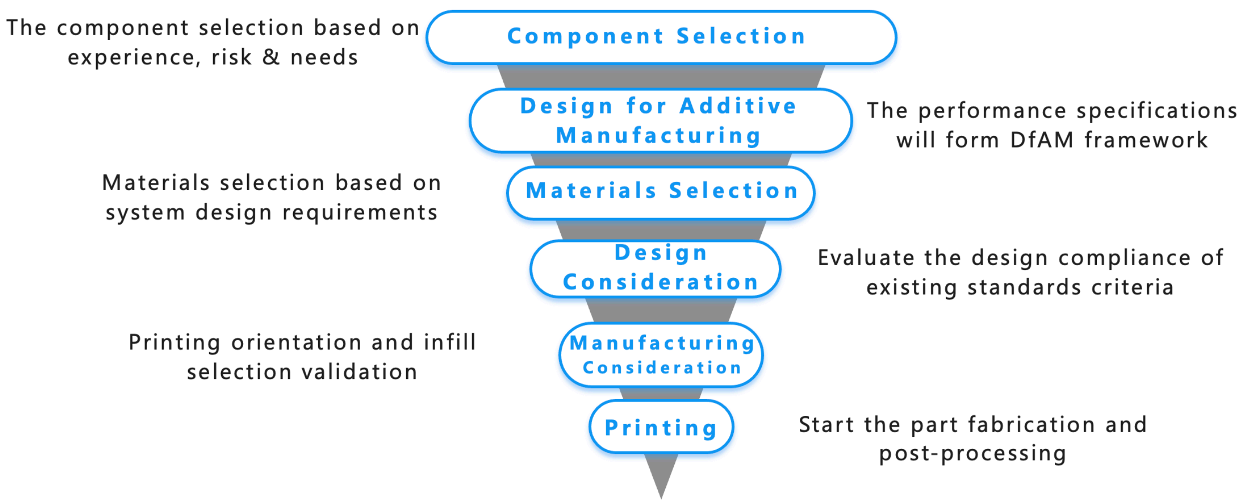

Figure 2 AM of Oil & Gas Component Creation Framework

Component Selection

Spacers and spectacle blinds are piping components used in any processing industry to retain a pressured piping loop. The primary function of these blinds is to isolate and shut down a flow in the case of spectacle blinds or to fill a gap between two piping flanges for piping spacers. Usually, blinds applications temporarily or permanently based on the piping system configuration and process requirements. ASME B16.48 is the governor standard to fabricate and manufacture the piping blinds/spacers for the installation between two pressurized piping flanges [4]. The fabrication for these blinds is either forged or casted steel for metallic piping. For nonmetallic piping, the current industry practice of nonmetallic piping systems is to use a steel-coated piping spacer between the piping flanges; if the coating fails, the part corrosion vulnerability is present. Another concern is over-torqueing leads to damage to the piping flanges. Based on this, the 3DP method is selected to fabricate the piping spacer with nonmetallic material that can suit the subject piping network. A specific case of study for a High-density Polyethylene piping loop is determined for an existing piping circuit to fabricate and manufacture a piping spacer. Table 1 shows the selected pipe specification and processing details.

Table 1 The Case of Study Piping Details

Pipe Specification and Details	
Pipe Material	High-density Polyethylene
Pipe Class Rating	150
Pipe Diameter	4”
Reference Standards	ASME B16.5, ASME B16.48
Fluid Type	Raw Water
Fluid Temperature	115F
Operating Pressure	175 PSI

Materials Selection

Materials selection involves various factors to make the final decision in manufacturing, such as application criticality, temperature, applied stresses, chemical compatibility, and anticipated failure modes. Polymers are the most commonly used materials in the 3DP as filaments to produce parts due to their ease of application and lower cost. 3DP uses filaments made of polymer: polylactic acid (PLA), acrylonitrile butadiene styrene (ABS), poly-ether-ketone (PEEK), etc. Some materials, such as ABS and PLA, have limited applications due to their lower mechanical properties. For instance, these materials can’t be utilized in aerospace applications. Instead, PEEK has superior mechanical and thermal properties to fit high-temperature surfaces [6].The material selection has its own cost. Thus, the materials are selected considering the part’s functionality and criticality. In general, pure polymers have lower mechanical performance. As a result, manufacturers tend to use composite polymeric materials (reinforced). In the context of fiber-reinforced polymers, there are two forms of fiber reinforcement: short fibers, and continuous fibers, impeded during printing to attain superior mechanical properties [7]. Continuous fibers are available with a longer length and control fiber orientation, while short fibers have shorter aspect ratios and generally are not fully aligned. Fiber orientation is vital in manufacturing since aligned fibers deliver higher strength than unaligned ones [8]. For this reason, continuous fibers are preferred from a strength standpoint. From a manufacturability aspect, the short fibers are much more appealing due to ease of production and lower cost. The common fiber used in the 3DP field are: carbon, glass, and Kevlar fibers. These fibers deliver higher stiffness in manufacturing with the matrix material after bonding [8]. Various polymeric materials with their composite mechanical properties were reviewed and analyzed from multiple resources with the aim of identifying the highest composite material performance. As indicated in table 2, it is clear that the 3DP composite filament tensile strength performance is much higher than pure polymers. The highest tensile value was on polymers reinforced with continuous fibers. Although continuous fiber impregnation delivers better mechanical properties, poor bonding is generated when the fiber content increases [9]. For this reason, the fabrication of continuous fiber reinforcement filament is very complex since it requires thorough control during processing. On the other side, the short fiber reinforcement avails a significant enhancement in the tensile strength by almost 45% versus pure polymers. In this case of study, the selected material was HPDE to fit the existing piping materials. As known HDPE crystallization and solidification process is very critical since failures such as warping, distortion and voids are present during fabrication. Due to the challenges identified in HDPE, the piping spacer materials will be utilized will pure and reinforced HDPE to evaluate the overall product cost and performance.

Table 2 Summary of Different Filaments with Their Reinforced Composite Materials

Materials	Pure polymer Tensile Strength (MPa)	Composite polymer Tensile Strength (MPa)	Fiber Type	Fiber Form	Ref
ABS	**32-43**	**63**	**Carbon**	**Short**	[11] [12] [13]
HDPE	**26.2**	**300.2**	**Carbon**	**Continuous**	[14] [15]
PLA	**46.61-65**	**241**	**Glass**	**Continuous**	[16] [7] [12] [9]
NYLON	**35.25**	**50.6**	**Carbon**	**Short**	[17]

Design for Additive Manufacturing (DfAM)

AM design consideration is fundamental while creating the desired printing model sliced to produce the final part. Not only the product's geometrical complexity and functionality are considered, but other factors such as quality, time, and the final cost are vital in designing for manufacturing. The design stage is a very critical and challenging task for AM producers because each new part will be created and evaluated based on its complexity, design criteria, performance specification, and application, making each manufactured part a unique product. (Wiberg et al.,2019) Defined and showed the design of AM automation application to be with three main stages: system, part, and process design [18]. The 3DP design process starts with the component design, where the component deficiency or problem, material, and anticipated load are considered while selecting the coveted printing method. Then, the part design follows the previous step by creating part initial design with interpretation and evaluating the need for the new part support structure. In this stage, verification is essential before proceeding with the processing to validate the created part design and ensure the design variables are examined. As shown in Fig 2, the overall design phases with an iterative and assessment process to optimize the final product design.

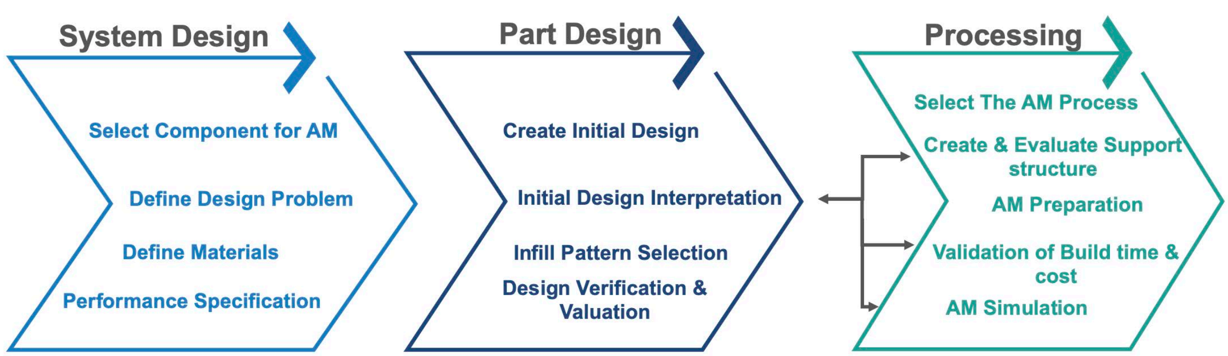

Fig 3 AM Design Phases Today Manufacturers Use.

AM preliminary design feature option is the overhang support structure. Generally, overhung structure design characteristics can only be achieved if the printing platform's inclination angle is above 45 degrees [19]. This is true because the self-supporting and overhanging are linked together with the difference in manufacturing platform angles. The supporting mechanism is defined as when the printing baseplate angle is less than 45◦ as overhang and self-supported if the angle is greater than 45 [19].

Design Consideration for FDM

Fused Deposition Modeling (FDM), or fused filament fabrication (FFF), is one of the most widely AM technologies currently used in the 3DP industry due to its simplicity, lower cost, and flexibility to fabricate parts with complex geometries. The FDM is a material extrusion-based process. In this process, the filaments are injected into a liquefier head and deposited with ultra-thin layers in a semi-solid state and solidify immediately to the previous layer formation until the final product is built [6]. The FDM 3D printed components are usually supported using a weaker material, and upon process completion, the support materials are removed, providing the final finished part [7]. Adhesion between printed layer elements and bonding of the deposited filament without facile detachment are the main factors that impose objects free of imperfections [8]. Without proper control of the printing process parameters, the tendency of voids formation is high, affecting the produced part strength compared to other traditional manufacturing methods. In this case study, the FDM process was selected to fabricate the part since the part materials that will be used is HDPE. The part design was started by selecting the required part size and dimensions. The piping component chosen was designed as per ASME B16.48 for steel piping components since no standards are available for nonmetallic. As shown in Fig 3, the selected piping component CAD design was developed and verified for any design uncertainties.

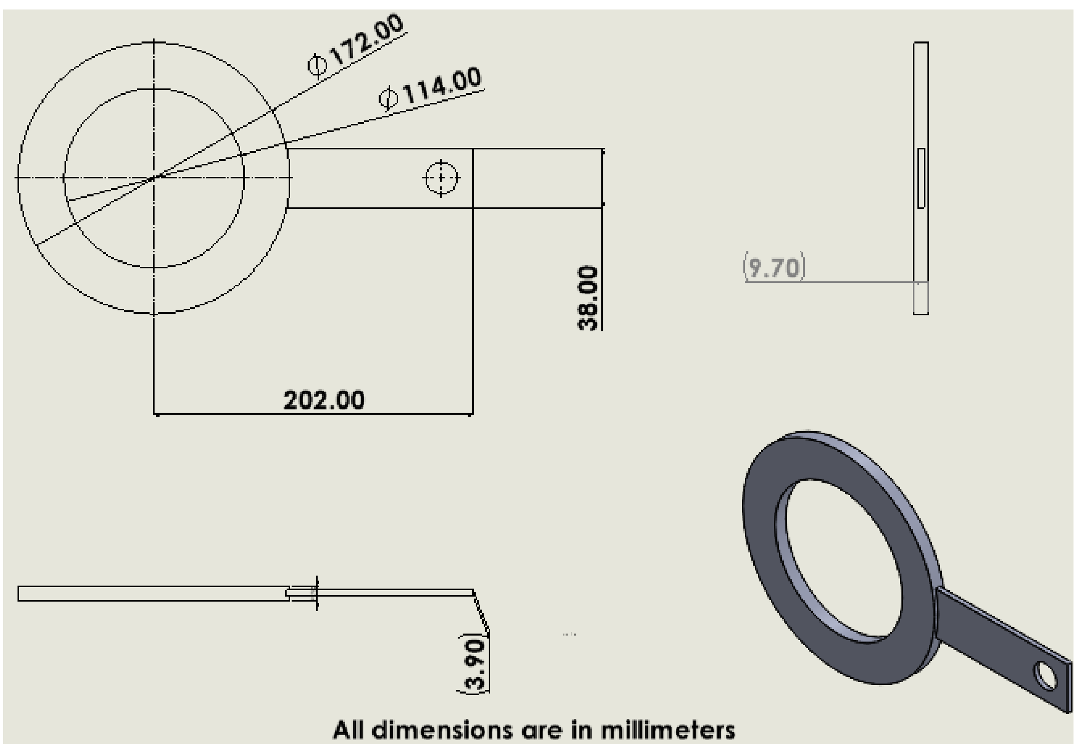

Figure 4 Isometric Drawing of The Piping Spacer

Manufacturing Consideration

Defects and imperfections are formed in manufacturing due to several causes, including but not limited to process parameter fluctuation, poor design, low-quality materials, and improper operation while producing new components. Thus, it is vital in manufacturing to understand and predict the product failure modes and defect formation to be addressed in advance before processing. In the FDM process, warping or distortion are the main issues that disturb FDM parts dimensions accuracy caused by the produced internal stresses in the manufacturing stage. These internal stresses rely essentially on the amount of volume reduction during the cooling phase from the glass transition temperature, precisely due to the discrepancy in cooling rates between different printed layers [20], [21]. Consequently, if the adhesion between the printed layers and the fabrication baseplate is enhanced using a suitable melting temperature, such defects can be avoided [21].Another quality concern impacting the part fabrication is improper feeding or extrusion. Basically, unsuitable extrusion, either over-run or under-run during the extrusion process, can cause a lack of adhesion, delamination, and debonding between the filament's layer, providing an uneven surface profile with dimensional deviations, porosity, and cracks [22], [23]. All these defects are profoundly affected by the printing process quality envelope. In-depth analysis of the main contributing elements for the FDM process are categorized, analyzed, and divided into two main domains: Printing Orientation and Infills.

Printing orientation and infills

Printing or building orientation is essential while producing AM components, particularly in the FDM process. The printing orientation is defined as the position of created part concerning the manufacturing machine coordinates within its printing platform. Build orientation is one of the main parameters that influences the staircase effect and the amount of support structure production. The stair-stepping effect is formed due to thickness differences between produced layers, which imposes deterioration in the surface quality of the final component [24]. As known, the stair-stepping effect can be reduced by controlling the thickness of the layer, leading to a more extended printing, which eventually will increase the production time. Infill density and pattern are the fundamental keys in 3DP, provoking designers to advance AM parts design seeking the lowest cost with the highest durability and reliability. This is not a straightforward equation that can be applied everywhere; several considerations shall be taken for part design based on its application for the final infill density and pattern. The infill density is described as the infill volume percentage using the deposited filament, where 0% is hollow, and 100% is a fully filled product [21]. Basically, the higher infill volume percentage delivers filled objects with upper strength limits; of course, this will impose extra material consumption, cost, and higher weight. For this reason, a well-organized design and production strategy is essential. In the FDM process, the infill strategy can be deployed at different sections of the created parts, such as the exterior shell or walls and upper and lower layers, by modifying each element independently, having a significant influence on the mechanical and physical properties. AM parts usually are not created with completely solid infill states, rather than with hollow internal structures to optimize time and cost in manufacturing. These internal hollow structures are produced with different structure geometry patterns: rectilinear, concentric, grid, triangular, gyroid, octet, cubic, quarter cubic, tri-hexagon, and stars patterns [21]. The desired infill pattern is selected based on the required strength, flexibility, and time. The concentric, grid, and honeycomb infill patterns provided the highest tensile strength due to their higher susceptibility to holding intermolecular deposits [25]. The part's mechanical characteristics heavily impact the infill density; as infill density increased, higher tensile strength and young's modulus were attained.

Conclusion

This paper outlines a case study of designing a piping component for process piping in the oil and gas industry. The DfAM framework demonstrates its effectiveness by minimizing iteration work at the processing stage. This design has the potential for deployment with any processing equipment. Utilizing this DfAM structure requires an investigation of the probability of risk failure for the selected part. The material selection and the part performance specification should integrate and automate at one stage to have an efficient and optimal design, avoid any constraints, and reduce the overall cost. The future work of this case study will focus on creating a piping spacer made of nonmetallic material suitable for outdoor applications that is compatible with the selected piping system specifications.

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