Fused Deposition Modeling 4D Printing Method

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The 4D fused deposition modeling (FDM) printing method is a futuristic technology that offers many advantages to the manufacturing industry. This type of manufacturing relies primarily on FDM and the ability of parts to transform their shape using advanced programmable materials. As a result, this technology needs to be studied closely, particularly in terms of resource consumption, which necessarily involves understanding the factors that influence the cost of manufacturing, in particular time and energy.

additive manufacturing (AM) fused deposition modeling (FDM) 4D printing materials energy consumption

1. Introduction

According to the Wohlers 2023 report, global growth in additive manufacturing products and services is estimated at 18.3%, with double-digit growth recorded over the past 34 years. The statistics from the same report confirm that there is a remarkable growth in materials, software, 3D printing services and hardware, with this growth rate being estimated at 23% in 2022 [1]. However, due to the large number of machines and production efficiency, the AM process has a low energy efficiency. In particular, for a short grinding process with long pauses, the energy consumption is higher, and the running time is more considerable [2]. This is why it has become crucial to design solutions that lead to optimized energy consumption for AM systems. Moreover, AM systems have a negative impact on the environment, and their effects can even have detrimental potential [3][4]. The study of energy consumption is useful for selecting the appropriate strategy and choosing the parameters to be adopted in 3D manufacturing. These parameters may be related to product design or shape accuracy but also to physical, mechanical, electrical, or thermal parameters [5].

In an additive manufacturing process, parts are formed by creating consecutive layers, with each layer representing a cross-section of the part. This process is based on CAD data transmitted to the additive manufacturing printing system [3][6][7][8]. On the other hand, there are seven types of additive manufacturing processes, classified on the basis of machine architecture. In addition, a number of standards are recommended for additive manufacturing, and to this end, an ASTM F42 committee meets twice a year to publish AM standards while also presenting work in progress. These standards help manufacturing specialists and machine manufacturers [9][10]. The seven processes of AM include the following: The vat photopolymerization (VPP) process uses liquid polymers that react to radiation by solidifying and ultraviolet light, which solidifies the liquid into layers.

Powder bed fusion (PBF) is considered one of the most versatile manufacturing processes, as it can be applied to metals and polymers to a lesser extent. This process uses a container filled with powder that is selectively treated with an energy source, typically a scanning laser or electron beam. The material jetting process (MJT) generally uses materials in a viscous state. It consists of selectively placing droplets of raw material on a platform, after which UV light is applied to create the first layer. This process continues with the creation of other consecutive layers and stops when the final part is formed. In the binder jetting (BJT) process, a bed with a layer of fine particles in powder form is used by selectively depositing a liquid binder to build up the high-value parts. This process is carried out by creating one layer after another, and at each stage, a cross-section of the part is formed. Sheet lamination is a process that joins sheets of material together to form a part, and the manufacturing process is performed by ultrasonic welding. Directed energy deposition (DED) is a directed process, since the melting of materials is performed by applying thermal energy. This melting is performed once the material is deposited in the system. Material extrusion is a technology that typically uses a polymer as the thermoplastic material and a heated nozzle to build the layers. Material extrusion is a technology that generally uses a polymer as the thermoplastic material and a heated nozzle to build up the layers. In this class of extrusion technology, the most popular process is FDM, in which the polymer is deposited in the system as a filament, and this polymer is liquefied via a reservoir in a heated state. The filament is deposited by pushing it into the reservoir via a “pinch roller”, whose role is to generate the pressure that extrudes the material [10][11][12][13]. Among the seven additive manufacturing processes, FDM is commonly used in 3D printing due to its excellent mechanical properties and a wide choice of materials, including thermoplastic polymers, ceramics and low-melting metals [10][14].

AM technology has a number of advantages in industry, including being a provider of sustainability, offering the possibility of creating customized prototypes, producing less waste and carbon monoxide gas and promoting a circular economy [15]. In comparison with subtractive manufacturing and bulk forming, a number of studies have been carried out in this field. Yoon, Lee et al. [16] examined three types of manufacturing: additive manufacturing, subtractive processes and bulk forming. The comparison showed that additive manufacturing is 100 times more expensive than bulk forming. This research showed that subtractive manufacturing processes have intermediate costs between the other two categories, which vary over a wide range, but the processes also vary in terms of scale. The researchers prove that the specific energy consumption of AM has a negative logarithmic correlation with productivity and concluded their study by pointing out that AM processes require more extensive evaluation of the environmental effect. David Rejeski [17] highlighted the potential environmental impacts of additive manufacturing, including waste generation, energy consumption, health risks, and life cycle impacts. In addition, the researchers provided evidence that additive manufacturing technologies consume more energy than conventional manufacturing technologies. Other research comparing the energy consumption between AM processes and conventional printing methods has shown that the specific energy consumption (SEC) of AM is one to two times higher than that of conventional methods. Moreover, only part of the environmentally oriented taxonomy has been documented with regard to AM processes, and most work focuses on energy consumption [8]. In this sense, the issue of energy consumption in AM has attracted the attention of many researchers [18][19][20].

The technologies of AM could support intellectualization and industrialization; moreover, AM systems are more complex, with multiple factors (structure, materials with physical and chemical considerations, cost, etc.); therefore, it is essential to study these systems based on artificial intelligence and big-data techniques [21]. In this context, several studies have been carried out to model energy consumption using machine learning [22][23][24]. However, it should be noted that for an FDM manufacturing process, there is not yet a model for predicting energy consumption and printing time that provides good results for optimizing these two costs while taking into account correct part orientation.

2. FDM 4D Printing

With the progress recorded in the development of 4D printing, 4D additive manufacturing looks promising for future work [25][26]. This technology can be successfully applied to expand several composite structures with shape memory, as in the case of 4D printing with “bi-stable” structures featuring intelligent responses [27]. Shape-memory polymer materials have additional functional capabilities that enable fourth-dimensional production, since these polymer-based materials are stimuli-responsive and have the advantage of modifying their shapes after printing has been complete [28]. In this context, several studies have investigated the use of these polymers in 4D manufacturing.

Bodaghi et al. [25] used double-layer encapsulated polycaprolactone (PCL) and thermoplastic (TPU) shape-memory composite structures 4D-printed for the first time. SME performance is studied by examining “fixity”, “shape recovery”, “stress recovery” and “stress relaxation” under flexural and compressive loading modes. On the other hand, the melting temperature of the PCL material, PCL and TPU influence the transition temperature, switching and net point, respectively. Taking into account the destruction of PCL, the dripping of this molten material and its contact with water, TPU encapsulates PCL, and this encapsulation offers a solution to the interlayer “bond/interface” while surpassing in the SME performance the bilayer printing of PCL-TPU. Subsequent experiments have shown that composites manufactured in 4D have a maximum stress recovery that does not change over time. The modulus of elasticity of TPU at the melting temperature of PCL is 16.5 times higher than that of PCL, because the latter has not been adapted to resist the release of TPU force, since the material has a behavior that is elastic in loading and recovery. Moreover, in the three bilayer and encapsulated structures, researchers find that the shape recovery values are 100%. In the compressive stress shape memory test, the highest temperature yielded a maximum stress value that did not decrease with time. Compared with extrusion-based SMP structures, the result of this research solves the problem of poor stress relaxation of previous SMPs. In [29], an adaptive metamaterial design with performance directly integrated into materials was investigated using FDM technology. The idea is to understand the thermomechanics of shape-memory polymers and the advantages offered by FDM for programming metamaterials that are self-folding. In this sense, five parameters that can influence material adaptation have been studied: “material”, “platform surface”, “relay-time” for printing each layer, “temperature”, “printing speed” and “liquefier temperature”. Given that the self-folding characteristic affects the change in shape and programming layer by layer, experiments have been carried out to determine how printing speed and liquefier temperature can affect this characteristic. In addition, a finite element (FE) formulation was used to provide a customized description of the materials in both the manufacturing and deformation phases. In this context, the combination of FE and FDM solutions was used to create straight or curved beams as structural primitives with the characteristics of being self-bending and self-winding. This 4D printing study demonstrated that adaptive metamaterials can be used to create prototypes capable of transformation in 2D or 3D and in several fields. This gives the advantage of designing and developing functional structures that feature “self-folding”, “self-coiling”, “self-conforming” and “self-deploying features in a controllable manner”. In [30], the parameters influencing 4D printing were studied, and these parameters mainly concern the design of the structure, the material, programming during printing and activation. In this context, FDM technology has been used with thermoplastic polymers as shape-memory materials (SMPs). These SMPs are printed in temporary shapes and then transformed into permanent forms under the effect of heat. In addition, material selection depends mainly on the shape-memory behavior of the filaments, while design is complex because of the freedom of design, and print programming depends directly on the printing parameters. For polymer activation, there are various methods, such as Joule or infrared activation, and these depends on the “amplitude”, “duration”, “support of the stimulus” and “stimulus environment”. In addition, it has been shown that activation parameters influence the transformation process, so a longer exposure time generates a greater amount of transformation, which reaches its maximum as the stress relaxes. For the activation temperature, the higher the temperature, the higher the velocity and the greater the transformation. Finally, the researchers confirm that planning, comparison and presentation of the structured design of experiments offer the presented 4D FDM model advantages in terms of long-term time savings.

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