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FEA OF ADDITIVELY MANUFACTURED COMPONENTS BY FUSED DEPOSITION MODELLING- A REVIEW

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Abstract: Additive manufacturing is an evolving technique used to produce complex products that are difficult to manufacture. Fused deposition modeling is a layer-by-layer production technique commonly used in industrial applications for rapid prototyping in product design and development. With the use of additive manufacturing technology, production of complex products is easily possible. Mass production of different types of products can be possible by the usage of additive manufacturing to achieve lead time and increase the production rate. Additive manufacturing has a wide range of applications, including automotive parts, in the aerospace industry and in the biomedical industry. Additive manufacturing is capable of improving and modifying the properties of materials by using reinforcement. The layer by layer of material deposition is an additive manufacturing process. It also helps to accommodate complex design, reduce waste of material and restore damaged parts of higher demands. The layer by layer production differs from traditional production and can have a major impact on material properties, which mainly affects material simulation modeling.

Keywords: FDM, Infill rate, PLA, ABS, ALT

I. INTRODUCTION

Additive Manufacturing (AM) is a layer by layer production technique which can transform CAD part directly into fully functional objects. This eliminates the need for post-processing before the desired final shape is reached. The greatest advantage of additive manufacturing is the unrestricted flexibility to model the complex part. Residual stresses and distortion issues are the drawbacks of additive manufacturing and post machining is also required, but AM generates less waste than traditional manufacturing is the greater advantage. We can predict the issues of distortion in numerical modeling and can minimize them by taking corrective measures. Such corrective actions are mostly taken when the model is already in production.

Fused Deposition Modeling (FDM) is the most widely used method of manufacturing for additive manufacturing in rapid prototyping. In FDM, a thermoplastic filament is deposited on a building surface by heating it to its melting point to build a three-dimensional structure. By using two pulleys, the thermoplastic filament is forced into the temperature-controlled extruder nozzle. The thermoplastic material is softened while passing through the extruder nozzle. The movement of the extruder nozzle and the table is computationally controlled. The extruder nozzle then follows a predefined 2D path to extrude the softened material andcreate the first 3D layer. The table then moves down to generate the second layer. This process goes on until the final three dimensional part is produced. One downside of this approach is that the part surface may have a step-like appearance depending on dimensional tolerance. Inconsistencies in the filament's diameter and density may also affect the extrusion of the product from the extruder nozzle, which affects the overall quality of the part.

The first step for simulations is to create the 3D printed part's CAD model. In FDM process, the solid CAD model developed in any CAD software is imported into open source slicer software that generates the appropriate G-code; depending on different parameters such as infill rate, infill pattern, layer height, etc. The information in the G-code describes the motion of the print head and determines other parameters used in the printing process, such as the temperature of the print head, the rate of printing and the quantity of material that is forced through the nozzle. G-code is the most widely used programming language for numerical control, which contains information about the actual model generated and depicts motions that are the actual physical behavior of the machine rather than the CAD model.

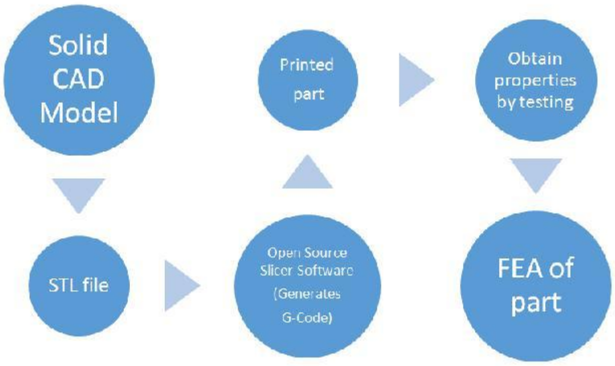

Fig. Flowchart of output property prediction and FEA of part

The part builds layer by layer using advance technologies of manufacturing is generally termed as additive manufactured part. Material removal by machining is generally referred to as subtractive manufacturing. In the additive manufacturing process, the layers are developed by adding material rather than by machining the material. G-codes created from the CAD model regulate the material addition process. The filament is typically a circular cross section with different diameters. The largest range of diameters is between 1.75 mm and 3.0 mm. By using the FDM process, we can produce different types of complex shapes without investing in dies and molds. Some of the complex shapes cannot be created using conventional production techniques, but canbe produced using FDM process.

II. THE EFFECT OF INFILL RATE

Yagiz Cicek et al carried out standard tensile experiments to characterize the average tensile strength, strain and elastic module of PLA components with different infill rates. They used PLA filament and Oo-kuma 3D Technologies and Ultimaker 2+ 3D to manufacture tensile test samples. Five samples were produced and tested at 25, 50, 75 and 100% infill rates. Components with different infill rates showed different characteristics in the plastic deformation region. Additional tensile experiments and improved material models are needed to improve the agreement between experimental results and numerical predictions.

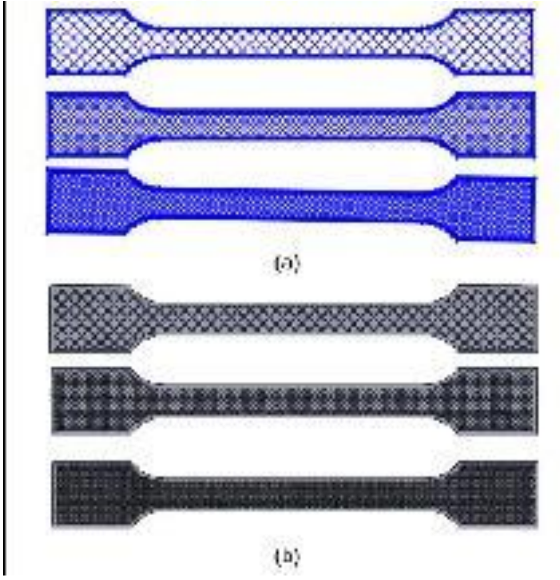

Fig. Infill rates are 25, 50 and 75% from top to bottom

The specimen's manufacturing orientation was in the same direction as the tensile tester's load direction. Samples consist of three boundary wall layers and a 45-degree grid within the sample. Simulations of the tensile experiment were also carried out in three dimensional finite elements. From simulation results, the appropriate expected properties of the 100% infill rate experiment are obtained.

Table: Average elasticity modulus, tensile strength and sample strain with different infill rates were obtained

Infill rate (%)	Modulus of Elasticity (MPa)	Tensile Strength (MPa)	Tensile Strain (mm/mm)
25	3458	60.2 (±1.0)	0.0230 (±14×10-4)
50	3534	57.9 (±1.9)	0.0240 (±28×10-4)
75	3816	64.4 (±1.2)	0.0240 (±5×10-4)
100	4174	73.0 (±2.2)	0.0230 (±14×10-4)

They usually found an improvement in tensile strength with an infill rate, but the infill rate of 50% showed lower tensile strength behavior. The reason for this behavior is not cleared at that point. To investigate this action, they suggest tensile tests with more samples.

III. THE EFFECT OF ORIENTATION OF PART

R.H. Hambali et al demonstrated the deformation behavior of the additive layer technology (ALT) components produced with different orientations. The deformation behavior of the ALT parts generated with multiple and different orientations were investigated. The value of the bracket's corresponding stress and deformation results were anticipated via physical testing and FEA. Sequences of tests have therefore been carried out to determine certain mechanical properties of different oriented component generated by FDM. They compared the material property results from the physical testing of fused deposition modeling (FDM) components which were designed in different orientations with the simulated analysis conducted using a finite element analysis (FEA). Simple specimen were designed and produced as a study test model and then digitally and physically tested. The test is carried out to examine the deformation behavior of FDM components produced in different orientations and to verify the design of FDM components using FEA analysis.

Fig. Orientations of brackets with the axis

They carried out tensile testing of various directed samples to obtain the orthotropic properties of additive layered parts. Test samples are developed in the form of test brackets displayed in the fig with three different directions. They developed five sample specimens for each orientation and used the ASTM D 638 standard for the geometry of the specimen. They tested all the samples using the Zwick Roell extensometer to obtain some of the mechanical properties value. After tensile testing measurements and calculations, some mechanical properties are obtained.

Table: Several mechanical properties of different orientations were obtained

Orthotropic Elasticity		Magnitude
Young's Modulus in X Direction	[MPa]	1904.000
Young's Modulus in Y Direction	[MPa]	2228.000
Young's Modulus in Z Direction	[MPa]	1822.500
Major Poisson's Ratio (XY)	[-]	0.157
Major Poisson's Ratio (YZ)	[-]	0.321
Major Poisson's Ratio (XZ)	[-]	0.127
Density	[kgm-3]	1020.000

During physical testing, the parts were found stronger when the direction of pulling was parallel to the direction of the building, but appeared to break in a specific location where the shear occurred. The useof ALTs is quite useful for immediate rapid prototyping applications but different oriented parts can show different deformation behaviors. They contrasted the stresses in each bracket orientation.

Table: Comparison of the outcomes of experiments and simulation.

Bracket orientation	Max. load [kg]	Max. Deformation [mm]	Max. Stress (Von Mises) [MPa]
XY direction (Experiment)	17	1.80	-
XY direction (Simulation)	17	1.65	40.32
XZ direction (Experiment)	31	6.28	-
XZ direction (Simulation)	31.00	2.95	78.30
YZ direction (Experiment)	32	2.21	-
YZ direction (Simulation)	32	3.03	83.47

From these results they determined that XZ and XY where the direction of construction was perpendicular to the direction of pulling load were weaker than YZ where the direction of construction was parallel to the direction of pulling load. This can also be represented using the FEA stress results. The maximum stress value of Von Misses for the YZ-oriented part was obtained as 83.47 MPa compared to all oriented parts. These values indicate that the design orientation of the components is one of the most important factors for structural components built using additive layer technology.

The orientation of the parts should therefore be chosen in accordance with the boundary conditions. In this analysis, however, the results of the FEA, which was developed with static and linear assumptions, indicate unison for bracket failure monitoring, so that nonlinear and dynamic FEA can be more appropriate for such investigations.

IV. SIMULATION OF EDAM PART

Bastian Brenken et al presented a developed structure for simulation of extrusion deposition additive manufacturing (EDAM), which is one of the most commonly used additive fabrication method. They used custom user subroutine suite for the simulation to replicate the EDAM process in Abaqus software. Based on the deposition head's temporal and spatial history from the component printing process, effectively dormant elements can be enabled using the latest UEPActivationVol user subroutine. The location and time history of the print head from the machine code was given to Abaqus software in the form of the event series. Abaqus software was provided with initial mesh and event series to simulate the printing process. Using the event series, dimensions and the layer height of the filament provided, only the relevant elements for the part were activated and the printed part was simulated similar to the actual printed part. The related printing history of the dormant elements outside the range of the deposited material bead has not been activated; thus, they have been ignored in the component simulation. The ORIENT subroutine is used to identify and implement printed material's anisotropic properties by assigning local element orientations based on event series details. The additional information obtainable for analysis in the event series was generated using the SDVINI user subroutine in the form of a user-defined state variable. To store and distribute the information required, the UEXTERNALDB subroutine was used.

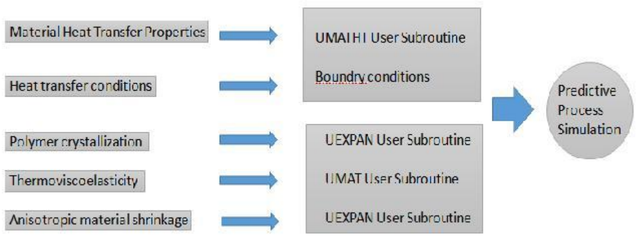

Fig. Flowchart of the Predictive process of simulation to model a part by using EDAM method

They represented the way to determine the element activation timing needed in UEPActivationVol subroutine and element orientations necessary for local orthotropic material properties in an efficient way to minimize the redundant controls by using the machine code that converts to an event series. This structure allows the simulation of multiple parts produced by the same machine by simply exchanging machine code and generating mesh files automatically. Both extensive material characterizations were carried out for a 50 weight percent carbon fiber reinforced polyphenylene sulfide (PPS) material and the desired material characteristics were used to model the part and were implemented in Abaqus software to replicate the EDAM process and to analyze the residual stress and deformation of the printed structure. In Differential Scanning Calorimetry (DSC) and laser flash experiments, the anisotropic thermal material properties were calculated and the printed part was analyzed using UMATHT user subroutine. The calibration experiment established the heat transfer conditions of the CAMRI printer and was included in the thermal heat transfer analysis. They also examined the kinetics of polymer crystallisation in which the behavior of thermoviscoelastic materials and anisotropic material shrinkage were calculated using suitable experiments and tests. The components were modeled using UEXPAN and UMAT subroutine. They calculated the residual stress and deformation of the printed components. The results of the validation suggested that the outcome was predictive by the simulation tool, which was able to predict both quantitative and qualitative residual stresses and deformations of parts printed using the EDAM process. The simulation tool that was previously developed can be considered a design tool that can help to reduce the time-consuming trial and error cycle of a successful print.

V. APPARENT DENSITY APPROACH

Ala'aldinAlafaghaniet. al examined the effect of the FDM processing parameters on the characteristics of the parts manufactured. The effect on mechanical properties and dimensional accuracy of building directions, print speed, extrusion temperatures, layer height, infill patterns, extrusion temperatures and infill percentage independently were investigated. In addition, they presented a new approach to modeling FDM components with FEA. It was shown that dimensional accuracy is more affected by the direction of building, the temperature offilament and the height of the layer than the infill pattern, infill rate and the speed of printing. They suggest that the critical dimension should be parallel to the layer orientation instead of the building direction, in order to improve dimensional accuracy for FDM components in a certain direction and dimensional improvement is also possible by using lower extrusion temperature and layer height. Mechanical properties have been observed to be significantly affected by layer height, construction direction and extrusion temperature, and less significantly by high infill levels, infill patterns and print speed. To improve the mechanical properties, a larger layer height and a higher extrusion temperature are needed, in addition to the proper building direction, which makes the layers and the load direction in the same plane. They used apparent density of FDM parts and established a new finite element analysis approach. It was shown that the FDM parts have gaps and porosities that can be observed in Scanning Electron Microscope (SEM) even at 100 percent infill rate.

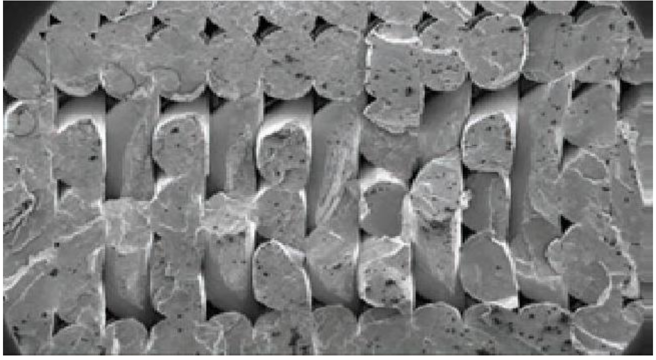

Fig. SEM image of specimen.

They measured the specimen by weighing it, and the water displacement method is used to measure the volume of the specimen. The apparent density is calculated by using mass and volume. In FEA, experimental data were used to determine the properties of the material and to determine the mechanical properties of the PLA filament, a tensile test was carried out. The created CAD model should compensate for the gaps or voids in modeling FDM parts in finite element analysis. Discontinuities in materials due to fusion layers are determined by the difference in densities for the finite element analysis of the CAD model. The diamond-shaped discontinuities are chosen with lengths 0.2 mm x 0.2 mm and which are perpendicular to each other, corresponding to the infill pattern of diamond and 45^0 raster angle. In the actual manufacturing condition of the FDM component, the discontinuity size is much smaller, which was used to reduce computational time and the need for finer meshing. They proposed adding the number of holes per area (HPA) using the formula.

$$\rho FDM = (V_{CAD} * \rho Filament - \rho Filament * l^2 * T * A_{CAD} * HPA) / VCAD$$

Where, ρFDM is the apparent density of the part, V_{CAD} is the volume of the CAD model, $\rho_{Filament}$ is the filament density, T is the thickness of the manufactured specimen, Length (l) is the length of discontinuity, A_{CAD} is the area of the specimen. Reduce length (l) and increase HPA to improve the accuracy of the model, but it will increase simulation time and also require a finer mesh. They clarified the need to use larger samples with lower infill rates to provide more room for infill patterns to emphasize the significance of infill patterns. They recommend that the use of the density ratio between the filament and the FDM component shows promising results, but the impact of the layers needs more improvements in both cases. They also recommend future directions for building more parts to investigate the effect of infill rates using larger samples where we can obtain better infill volume than shells and to explore the effect of infill patterns with lower infill rates.

VI. CRACK ANALYSIS

J. Li et. al investigated the fracture of polymers which are additively manufactured and also studied possible toughening mechanisms computationally as well as experimentally. It was very difficult for them to capture all possible crack paths and other details due to the inter-filament welding lines that are broadly distributed and arranged differently between layers. They used the extended finite element method (XFEM) that was built in the ABAQUS program with a cohesive segment approach. The advantage of this method is that it allows crack propagation within finite elements and, as a consequence, the crack direction should not be predefined or the mesh details should not be changed in advance. They used ABS material to fabricate single edge notch tension specimens by using fused deposition modeling with different building orientations. The horizontal build orientations are 45°/-45° and 0°/90° raster angles and the vertical orientation of the building has layers perpendicular to the 0°/0° notch. An anisotropic damage model in concurrence with the cohesive segment approach and the extended finite element method (XFEM) is used to capture fracture behaviors mentioning building directions. To evaluate the crack growth, the maximum principal stress failure and the anisotropic damage along the direction of inter-filament are taken into account jointly, which is then capable of capturing the alternating crack kinks found in 45-45 samples. Numerical parametric observations of cohesive strengths for both criteria further illustrate that the inter-filament bonding can be modified to optimize the total energy dissipated in the additive manufacturing polymer fracture. In addition, toughening mechanisms that are available in experiments utilizing 3D printed topological patterns on the sample surface are also investigated. The patterns generated effectively delay crack initiation and prevent crack propagation, resulting in enhanced fracture properties.

VII. CONCLUSION

We can conclude that tensile strength of specimen varies with the infill rate and other factors like layer height, infill pattern, extrusion temperature and printing speed. For better dimensional accuracy we should use lower extrusion temperature and lower layer height. When the pulling direction is parallel to the build direction, the parts are stronger, but they tend to crack in a specific place where the shear occurred. Tensile strength of PLA material is greater than ABS.

FUTURE WORK

Additional tensile experiments and improved material model are necessary to improve the agreement between experimental results and numerical predictions.

The effect of the combination of different parameters, such as infill patterns and infill rates, should be investigated.

Lamina material properties can be used to simulate the model instead of using isotropic material properties.

To study the stress relaxation during build, characterization of viscoelastic behavior of the composite material should be investigated.

The study of parameters such as cooling rate and environmental conditions are needed.

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