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An insight to the failure of FDM parts under tensile loading: finite element analysis and experimental study

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ABSTRACT

Fused deposition modeling (FDM) is one of the widely adopted additive manufacturing techniques to fabricate complex three dimensional parts to a near-net shape. FDM parts are now-a-days not limited to prototype building for product realization but used as functional parts in widespread applications. The present work aimed at unveiling the deformation behavior of the FDM samples in general and individual rasters of different thicknesses (layer thickness), in particular, laid at different directions under uniaxial tension. Finite element (FE) analysis is carried for FDM tensile specimens to simulate elasto-plastic behavior and results are validated with the experimental observations. More realistic models for FE analysis are generated that include the layers of different thicknesses (0.178 mm, 0.254 mm, 0.330 mm) and rasters at different angles (0°, 90°, 0°/90°) maintaining the inter-layer and intra-layer bonded region (developed in the present work). FE analysis and experimental results indicate that developed stress, strain at yield, elongation and tensile strength first decreases with layer thickness and then increases. Number of layers along the loading direction is more in sample with 0.178 mm layer thickness thus more elongation and load bearing capacity whereas for 0.330 mm layer thickness, less number of air voids and higher intra-layer bonded region are the reasons for higher tensile strength of the specimen. FE results and fractographic analyses reveal that first failure and layer separation in 90° rasters occurs followed by brittle failure of 0° rasters where pulling and necking takes place. Results also show that 0° raster layers fail under pulling and rupture of fibers and numerous micro-hills indicating micro-pulling of each raster fiber within a layer of material are the reasons for the improved tensile strength for 0° raster specimen.

1. Introduction

Rapid prototyping (RP) has become focus of manufacturing in recent years to accommodate part complexity and fabrication of parts within the time and cost constraints. Fused deposition modeling (FDM) is one of the widely adopted RP technique for fabricating three-dimensional (3D) complex components by depositing the material layer by layer through a very fine liquefier nozzle that moves in X and Y direction (in the plane of build platform). After depositing one layer, the build platform (or the worktable) is lowered in Z direction and the next layer is added. In FDM technique, the model and support materials are deposited through a separate liquefier nozzles mounted on the extrusion head. To fabricate components without much geometric distortion, the parts are built with simultaneous deposition of support materials at desired locations. The deposited support material can be removed easily once the fabrication is complete and the part is taken out of the build chamber. Both model and support structure materials are available in the form of filaments which melt at preselected temperature before deposition. The deposited material solidifies rapidly and adheres to adjoining layers due to thermally driven diffusion bonding [1].

In FDM process components' mechanical strength (like tensile, flexural strength) and surface roughness are observed to be highly anisotropic [2,3]. Strength, roughness and geometric accuracy of the final manufactured parts depend on various process parameters such as contour width, raster angle, raster width, layer thickness, part orientation, air gap and machine settings [4]. Selection of optimum process parameters settings can improve the mechanical strength, surface roughness and geometric accuracy to considerable amount. The influence of model material temperature, raster width, air gap, raster angle and material colors were investigated on tensile and compressive strength of ABS P400 FDM samples [2]. Garg et al. [3] investigated the effect of raster angles on tensile strength, flexural strength and surface roughness of FDM parts. Results revealed that 0° raster angle offers more mechanical strength than 90° raster specimen. The influence of air gap, part orientation, raster width, layer thickness and raster

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angle was investigated on the tensile, flexural and impact strength of FDM parts using statistical approach [5]. Croccolo et al. [6] investigated the effect of part build directions, number of contours on tensile strength and stiffness of FDM parts using both experimental and analytical modeling techniques. They proposed analytical model to predict the failure of FDM samples considering the FDM parts as slender beam and sharing the load between longitudinal and inclined rasters and validated with experimental results with mean error reported as 4%. Espin et al. [7] investigated the effect of part orientations on the tensile strength of polycarbonate parts fabricated by FDM technique and verified the results with finite element method. They concluded that mechanical strength of FDM parts are anisotropic in nature and depend upon part building direction. To increase the mechanical strength, the part should be orientated in such a direction that produces longest contours aligned with tensile stresses. However, the other process parameters such as raster angle, layer thickness etc. also significantly affects the mechanical strength of FDM parts and needs to be modeled for detailed study. Huang and Singamneni [8] carried out analytical modeling considering a hypothesis that mechanical properties of FDM parts are structure sensitive in nature. They studied the influence of raster angles on the tensile strength, shear modulus, elastic modulus and Poisson's ratio of FDM parts. Results showed that mechanical strength decreases with increase in raster angle from 0° to 90° which are also validated with experimental observations. The influence of layer thickness, scanning speed and road width was investigated on the distortion and residual stresses of FDM samples using finite element based thermo-mechanical model [9]. The results showed that scanning speed has significant effect on the part distortion whereas residual stresses increases with increase in layer thickness. Bellehumeur et al. [10] studied the influence of envelope (build chamber) temperature, extrusion temperature and width of extruded filament on bond quality and neck formation between adjacent filaments in FDM process and found that extrusion temperature is most significant factor the effects the neck growth and bonding. Ravari et al. [11] investigated the effect of struts diameter on elastic modulus and collapse stress of cellular lattice structure fabricated by FDM process using finite element method. The influence of raster orientation was investigated on tensile, flexural and impact strength of FDM parts [12]. They observed that failure of the specimen mainly occurred along the layer interface. The effect of building direction and model interior on volumetric shrinkage and tensile strength was investigated for FDM parts using multi-objective optimization technique [13]. They further investigated the effect of inter-layer bonding, intra-layer bonding and neck formation between adjacent filaments on tensile strength of FDM parts using both experimental and mathematical modeling [14]. They observed that in a FDM sample with 0° raster layers the failure of a specimen is due to inter-layer fracture whereas in 45° raster layers, specimen fails under both inter-layer and intra-layer fracture. Dawoud et al. [15] investigated the effect of raster angle and raster air gap on mechanical strength of FDM parts and found that negative air gap significantly improved the mechanical strength of FDM parts. The influence of part build direction and raster orientation was investigated on tensile strength, tensile modulus and elongation of FDM samples [16]. The relationship between failure and mechanical properties are derived through fractographic analysis.

Aforementioned literature review reveals that several authors have made attempt to determine the optimal process parameter settings to obtain desirable mechanical strength of FDM parts. The FDM parts, may it be the functional parts or prototypes, behave differently under loading condition and depend upon the layer thickness and alignment of the rasters with respect to loading direction [3]. Adaptive layer thicknesses [17], depending upon part shapes and structure, could optimize the surface roughness but may affect the strength of the build parts non-uniformly. Few authors have also studied the effect of process parameters on the performance of FDM samples through finite element methods [7,9] however, finite element models that accounts for the layer pattern with their orientation and thickness can effectively predict the behavior of the FDM specimens. Thus, the present article is aimed at providing an insight towards the behavior during tensile failure of FDM samples built at different raster angles and layer thicknesses. In order to study the elasto-plastic behavior of the individual raster, their orientation, layer thickness, realistic FE models are developed that include the layers of different thicknesses (0.178 mm, 0.254 mm, 0.330 mm) and rasters at different angles (0°, 90°, 0°/90°) maintaining the inter-layer and intra-layer bonded region and subsequently results are validated with experiments. Later, fractographic analyses are carried out using optical microscope, 3D optical profiler and scanning electron microscopy (SEM) to study the failure modes of FDM samples.

2. Materials and methods

2.1. Finite element modeling

In the present work, finite element modeling and simulation are carried out for acrylonitrile butadiene styrene (ABS) FDM specimen using finite element (FE) package ABAQUS. The samples are designed at three different layer thicknesses (0.178, 0.254 and 0.330 mm) and three different raster angles (0°, 90° and 0°/90°) using Pro/Engineer 5.0 CAD modeling software. The created models are exported to ABAQUS in STEP file format. The overall dimensions for tensile test specimens

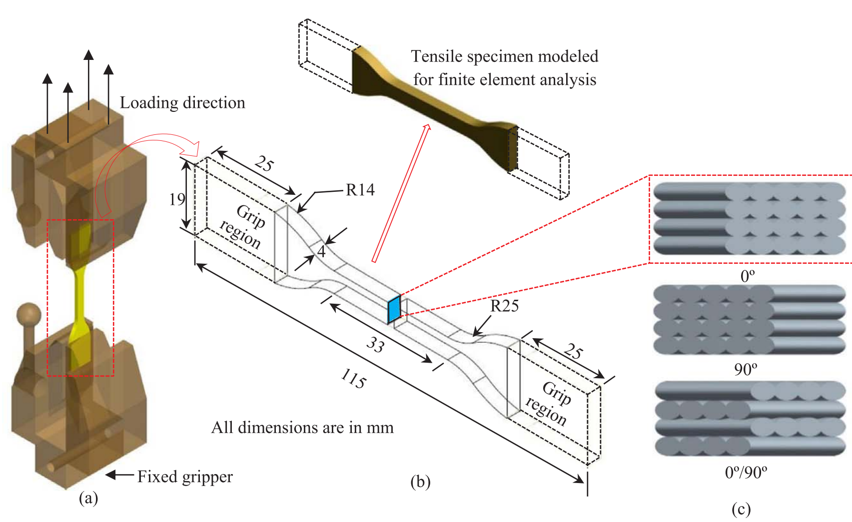

Fig. 1. (a) Schematic of gripper arrangement, (b) tensile specimen as per ASTM D638 standard, (c) schematic illustration of different raster angles.