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Dynamic stress-strain compressive behaviour of FDM made ABS and PC parts under high strain rates

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Abstract. This paper presents an investigation on dynamic compressive behavior of ABS and Polycarbonate (PC) parts fabricated by Fused Deposition Modelling (FDM) additive manufacturing process when such parts are subjected to high strain rate loading conditions in engineering applications. Split Hopkinson Pressure Bar was used to carry out high strain rate compression tests on cylindrical test specimens fabricated by the FDM process using different FDM process parameters. The dynamic true stress-strain curves at high strain rates were compared with quasi-static curves obtained from static compression tests at low strain rates. Results of dynamic compression tests show that FDM process parameter of build style has significant influence on the dynamic response of FDM made ABS and PC parts under high strain rate loading. FDM made PC materials exhibit higher compressive stress than ABS material under static and dynamic conditions. FDM parameters also affect the static compressive strength for both materials.

1. Introduction

Fused Deposition Modelling (FDM) has grown rapidly to be one of the most popular additive manufacturing technologies. FDM is an ideal technique for conceptual modelling, engineering design and making parts for design investigations such as prototyping or functional testing. It is also attracting interest in rapid manufacturing of small lots of plastic components [1, 2]. In the basic FDM process, parts are fabricated by using a thermoplastic feedstock filament through a liquefier head to extrude and deposit the semi-molten material through a nozzle to create parts in a layer by layer building technique. Currently available commercial Stratasys FDM systems can fabricate parts in a range of engineering thermoplastics such as ABS, Polycarbonate, ABS/PC, Nylon and Ultem [1].

Knowledge of the mechanical properties of parts fabricated by Fused Deposition Modelling (FDM) additive manufacturing (AM) technique is essential for engineering applications of such parts. The strength and quality of FDM processed parts depend greatly on various FDM process parameters selected during the fabrication process. It is critical to understand the material properties of the FDM fabricated material and the effect of FDM build and process parameters on material properties under various loading conditions in order to predict the mechanical behaviour of FDM fabricated parts.

Recently, there has been an increased interest in the development of high strain-rate testing for a variety of materials using Split Hopkinson Pressure Bar (SHPB) apparatus [3]. In this method, as described later, a cylindrical test specimen is placed axially between two long bars and a stress wave is passed through the specimen generated by high strain rate loading at one end of the bar. The resulting incident, transmitted and reflected stress wave signals at the specimen are recorded to generate dynamic stress-strain curves at various strain rates dictated by the impacting load at the bar end. This technique has the potential to dynamically characterize a large range of materials, both metals and non-metals, as well as brittle, ductile and soft materials. Several studies have been made to investigate high strain rate compressive behaviour of various conventionally processed metals and alloys using the Split Hopkinson Pressure Bar (SHPB). Song et al [4] have used Split Hopkinson Pressure Bar apparatus to investigate the compressive properties and strain-rate sensitivity of several die cast magnesium alloys. Lee and Kim [5] have used the SHPB technique to study the dynamic behaviour of aluminium alloys in tension and compression mode and PMMA in compressive loading conditions. Khan et al [6] have used the technique to study the dynamic response of titanium alloys at different strain rates and different temperatures. Some studies have also been undertaken to apply SHPB technique for polymers. Chen...
et al [7] have used the technique to study the dynamic behaviour of epoxy and PMMA polymers in tension and compression at various strain rates. Siviour et al [8] have used the SHPB method to investigate the high strain rate compressive behaviour of polycarbonate and polyvinylidene difluoride polymers at various temperatures and strain rate values. Okereke et al [9] have applied the SHPB technique to investigate the dynamic compressive behaviour of three grades of polypropylene at room temperature across a wide range of strain rates.

It is noted that very little work has been reported on investigating the high strain behaviour of materials processed by additive manufacturing using SHPB. Owolabi et al [10] investigated the tensile properties and dynamic response of ABS parts made by FDM process at different strain rates, but did not consider quasi static compressive response. Chaudhry et al [11] studied the performance of 3D printed polyurethane plastics under quasi static tension and dynamic loading at different strain rates with varying printing parameters. In order to widen the application of 3D printed polymers in dynamic loading conditions, more in-depth understanding of high strain rate behaviour of 3D printed parts of different engineering plastics is required. Polycarbonate (PC) and ABS are two important thermoplastics used in Fused Deposition Modelling AM systems with wide range of functional design applications. In many such applications, the FDM made parts are subjected to withstand high strain rate deformation.

This paper presents an investigation on the dynamic behaviour of ABS and PC thermoplastics processed by Fused Deposition Modelling additive manufacturing technology with varying FDM process parameters. The Split Hopkinson Pressure Bar (SHPB) apparatus has been used to study the compressive behaviour of FDM processed specimens under high strain rates and compared with static compressive behaviour of the same specimens conducted under normal compression tests. The strain rates of the order of $10^{-3}$ s$^{-1}$ and $10^{3}$ s$^{-1}$ were applied for static and dynamic tests respectively in this study. The work presented helps to understand the dynamic behavior of FDM made thermoplastics components subjected to high strain rate loading.

2. Materials and Methods

In order to determine the static and dynamic mechanical properties of FDM polymer specimens at high strain rates, several solid cylindrical test specimens were fabricated by Stratasys FDM Vantage machine. The FDM Vantage machine has a number of parameters, which affect the part strength and mechanical properties. The main parameters considered in this study are the build style, raster width, and raster angle. The meaning of each of these parameters are described in detail by Masood [1]. The effect of these parameters on static and dynamic behaviour will be studied for two types of FDM materials ABS and PC.

Test pieces were made from feedstock Stratasys ABS and PC materials using specimen size of 10 mm in diameter and 4 mm height. Table 1 shows the three sets of three FDM parameters selected for each ABS and PC samples. For each set, four test samples were tested for averaging the results of dynamic testing. Thus a total of 24 FDM specimens were created and tested with 12 specimens each for ABS and PC. Parameters were selected such as to compare the effect of main build styles and raster width for the two main materials. Thus for each material, same raster width was used for two build styles (sparse and solid normal), and same build style was used for two raster width (0.4064 mm and 0.8319 mm). Raster angle was kept constant at 90º for all samples in order to reduce the number of tests and to investigate effects of only two FDM process parameters - build style and raster width. Same scheme of testing was adopted for static compression test as described later.
### Table 1. FDM Process Parameters of Specimens

| Material                  | Raster Width (mm) | Raster Angle (degree) | Part Build Style |
|---------------------------|-------------------|-----------------------|------------------|
| Acrylonitrile butadiene styrene  
(ABS)                         | 0.4064            | 90°                   | Sparse            |
|                            | 0.4064            | 90°                   | Solid Normal      |
|                            | 0.8319            | 90°                   | Solid Normal      |
| Polycarbonate              
(PC)                         | 0.4064            | 90°                   | Sparse            |
|                            | 0.4064            | 90°                   | Solid Normal      |
|                            | 0.8319            | 90°                   | Solid Normal      |

#### 2.1 Dynamic Compression Test

High strain rate compression tests were performed using a Split Hopkinson Pressure Bar apparatus. Figure 1 shows a schematic diagram of the Split Hopkinson Pressure Bar set up. The set up consists of an incident bar and a transmission bar each 1 m long and 13 mm diameter and made of high strength steel. The test specimen is sandwiched coaxially between the two bars. Specimen of aspect ratio (height/diameter) smaller than 1 is normally used in dynamic testing. In this experiment an aspect ratio of 0.4 was used to facilitate dynamic stress equilibrium in the low impedance materials used in this study. Contacting surfaces of the specimens and the bars were lubricated to reduce the friction effect. A movable strike bar is made to hit the incident bar co-axially with impact velocity ranging from 10 m/s to 30 m/s. Higher impact velocity will generate higher strain rates. In the current study strain rates of around 3000 /s were used. When the strike bar impacts the incident bar, an elastic compressive stress wave is generated and travels through the incident bar. When it reaches the specimen, a part of the stress pulse is transmitted to the transmission bar and a part stress pulse is reflected back into the incident bar. The stress pulses are recorded by the strain gauges fitted at the middle of the two bars. The signals from the strain gauges are amplified and recorded by high speed digital oscilloscope. The relative magnitudes of these incident, reflected and transmitted strains are combined to generate the dynamic stress strain curve for the specimen [12]. Figure 2 shows the magnitudes of incident, reflected and transmission pulse obtained from the incident and transmitter bars for ABS specimen. Similar graph was obtained for the PC specimen. From this data set the strain rate vs strain is calculated and plotted as shown in Figure 3.

![Figure 1. Split Hopkinson Pressure Bar test system](image_url)
Figure 2. Strain gauge output versus time graph for ABS sample

Figure 3 shows the comparison of strain rate versus true strain for ABS and PC samples of FDM solid normal and sparse build styles. The average strain rates of 3100 s\(^{-1}\) to 3300 s\(^{-1}\) are captured during SHPB testing. In general, the solid normal build style offers a higher strain rate compared with the sparse build style for both cases of ABS and PC samples. The PC solid normal sample has the highest average rate of 3300 s\(^{-1}\). It seems that strain rate behaviour of specimens are dependent on the strength of material. It is also noted that all graphs reach their peak early and their performance continues to be stable until they reach the fracture point.

Figure 3. Comparison of strain rate versus true strain for ABS and PC samples

2.2 Static Compression Test

Static compression tests were conducted using MTS Criterion model 43 testing machine to study the mechanical behaviour of polymers under low strain rate (10\(^{-3}\) s\(^{-1}\)). The deformation speed was set to 0.5 mm/min. The same size test samples and the same testing scheme were as used for dynamic testing as described in Section 2.2 and in Table 1. Thus four test samples were tested for averaging the results of static testing for each of the three cases for ABS and PC. Engineering stress-strain curve is derived from load and deflection and then true stress versus true strain curves were derived using a constant volume assumption. The results will be compared with high strain rate test results in order to assess the effect of high strain rate on mechanical behaviour of polymers. The optical microscope was used to study the fracture behaviour in static and dynamic tests.
3. Results and Discussion

3.1 Static and Dynamic Compressive Behaviour

Figure 4 shows a general view of all six dynamic and all six static compressive true stress strain curves for the two types of FDM made polymers: ABS and PC for various build styles and raster widths.

In static compression tests, all six curves exhibited typical nonlinear viscoelastic behaviour followed by yield and plastic flow commencing at approximately 10% true strain for ABS and at around 15% true strain for PC material. Static curves follow linear behaviour in all cases before passing yield point. However, yield point is different for PC and ABS. After yield point, the stress-strain behaviour changes to plastic deformation, with higher stress values for PC than for ABS. In static tests, PC achieved a higher yield stress of approximately 40 MPa at a higher strain while ABS achieved a lower yield stress of around 25 MPa at a lower strain. Closer observation of the static results indicate some of the fundamental behaviour of the typical compressive testing of polymers: linearly elastic, non-linearly elastic, yield stress onset and large plastic flow. FDM parameters of build style and raster width had very little influence on static stress strain curves of PC and had almost no influence on the static strain curve of ABS material. However static normal build style and lower raster width tend to increase the static stress values for the PC material.

As shown in Figure 4, the dynamic stress strain curves under high strain rates show marked difference in the two materials and the effect of FDM process parameters was also dominant. The dynamic curves show more fluctuations in stress values than in static tests. During dynamic compression, adiabatic heating occurs in the specimen associated with large inelastic deformation. This factor may reduce brittle-ductile transition behaviour normally caused by the strain rate effects. All compressive tests, both static and dynamic, displayed ductile failure mode as indicated by global barrelling of the specimens. There was no brittle-ductile transition observed in the dynamic tests. The dynamic compressive strength for PC was much higher than the dynamic compressive strength for ABS material. The yield stress observed for PC specimen in dynamic test was around 80 MPa, which is twice that of static yield stress of PC and also occurred at much less strain deformation compared to static test for PC. The dynamic yield stress for ABS was around 60 MPa, which is much higher than the static yield stress for ABS but it occurred at slightly less strain than that in static test. Considering the effects of FDM parameters, it is noted that solid normal build style tends to increase the dynamic compressive strength both for PC and ABS, while raster width does not tend to affect the dynamic compressive strength for both materials. In summary, the most prominent feature of the compressive behaviour of both ABS and PC materials is the significant rise in the yield stress at high strain rate relative to the yield stress at quasi-static strain rate.

Figure 4. Dynamic and Static true stress-strain curves for PC and ABS with FDM parameter
Figure 5 shows a sequence of quasi-static deformation of ABC and PC with time duration under compression loading at strain rate of 0.001 s\(^{-1}\). It is noted that at low strains (below 20%), the difference in stress between the ABS and PC samples is very small for all six cases of testing. However, beyond this strain, the barrelling effect was observed in samples and a significant difference in stress values were observed with PC samples showing larger compressive strains than the ABS samples. This difference is even smaller for variation of FDM parameters for the same material. Beyond 75% strain it was difficult to assess barrelling because of smaller size of samples under deformation. The specimens were observed to undergo ductile deformation during the dynamic and static testing.

![Figure 5. Sequence of Quasi-static Compressive Deformation for ABS and PC samples](image)

3.2 Deformation Behaviour

Test samples were examined by optical microscope for deformation behaviour before and after testing. Before observation, care was taken to make the edges sharp and clean using an ultrasonic cleaner and an appropriate cleaning solvent for the samples. The samples were examined using a Leica research optical microscope fitted with a digital camera. Figure 6 shows optical microscope views of FDM made original PC sample, the sample after static compression and the sample after dynamic compression. Samples show barrelring effect which confirms generally ductile mode of deformation for static and dynamic testing. It is observed that stress caused by compressive loads make some fracture in edges of static sample as shown in Figure 6(b). Investigation on dynamic compression test sample show the higher deformation as shown in Figure 6(c). It seems that high strain rate influence has caused a shear on joint line of deposition layers in dynamic compression test.

![Figure 6. Optical microscopic views of FDM made PC sparse style: (a) original sample (b) sample after static compression, (c) sample after dynamic compression](image)
Figure 7: Optical microscopic view of PC dynamic test sample cross section

Figure 7 shows the optical microscopic view of the inside cross section of the PC dynamic compressive test sample with solid normal build style. The figure shows cleavage of the bondage between the molecules making the surface softer after the dynamic compressive deformation, which leads to reduction in hardness values of all dynamic test samples compared to hardness of static test samples.

4. Conclusions
In many engineering applications, the FDM made parts are subjected to withstand high strain rate deformation. Therefore this paper has presented an experimental study to understand the dynamic response characteristics of FDM fabricated samples made with different FDM process parameters of build style and road width and under high strain rate loading using Split Hopkinson Pressure Bar. Results show that both ABS and PC displayed ductile behaviour during high strain rate dynamic compression as well as during low strain rate static compression. Significant increase in yield stress was observed under high strain rate loading compared to static compressive testing for both materials and for all FDM process parameters. It was also observed that not all FDM parameters have impacted on the static and dynamic response characteristics. The FDM parameters vary in their influence on each proposed response characteristics. The build style has shown to significantly influence the rigidity of the FDM build part. The solid normal build style provides better strength than sparse build style, while raster width had little effect on static or dynamic properties of FDM parts. Optical microscopic study has provided evidence of more deformation and fracture of ABS compared to PC under static and dynamic types of loading conditions. These images also provide an evidence of better stability of PC under dynamic compression loading conditions.

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