An investigation into the secondary stage creep behaviour of ABS thin-walled additive manufactured specimens.

Robert Benham[1], and *Fayyaz* Rehman[2]

[1]Department of Engineering, Computing and Mathematics, University of Chichester, College Lane, Chichester, West Sussex, PO19 6PE
[2]Department of Science and Engineering, Solent University, Southampton, Hampshire, SO14 0YN

Abstract. Advances in additive manufacturing (AM) technologies have resulted in a much wider choice of materials and recently improved quality of AM components with fewer rejected parts. Although research into the material properties of additive manufacturing materials is well established, there are still challenges in the production of some complex geometries and thin-walled parts. Uncertainty in the behaviour of these parts requires testing, which includes time-dependent behaviour and at elevated temperatures. Creep testing provides a way of observing this behaviour of thin-walled specimens. This study looks at a comparison of ABS test specimens using two different types of in-fill and various in-fill densities. Whilst there are many variations of in-fill and build options which are not included, this study provides a pilot investigation which can be used for more extensive testing for other AM materials and shapes.

1 Introduction

Additive manufacturing (AM) has experienced a recent large increase in demand for small printers for both home use and commercial environments, with entry-level printers proving to be very popular. Whilst there have been some good improvements in the quality of recent and emerging low-cost 3D printers to the market, there are still several challenges that need to be addressed. Material extrusion is one of the main AM technologies is classed as fused filament fabrication (FFF) which is suited to a range of filament materials. This study selects acrylonitrile butadiene styrene (ABS), but other types are available such as polylactic acid (PLA), acrylonitrile styrene acrylate (ASA), thermoplastic polyurethane (TPU) as well as a range of composite filament materials. Tensile testing data is widely available, based on ASTM D638 test specimens. However, the behaviour of thin-walled components cannot rely on standard tensile data [1], as well as the level of uncertainty in the time-dependent behaviour for these parts. Whilst it is undesirable to produce extremely thin sections of these parts, there is a lack of testing data for the creep behaviour of thin-walled specimens for some materials, although a few recent studies have looked into creep recovery of AM materials, Gebrehiwot *et al* have reviewed PLA for both AM and injection-moulded specimens [2] with relatively high in-fill densities and focused on in-fill direction as a main variant. Other studies investigate improving creep resistance of AM composites [3]. The scope of potential research in this area remains large, especially as newer, improved advanced polymers come on the market. Given the level of interest in the properties of AM materials in recent and current research, it is beneficial to conduct a pilot study into the creep behaviour of thin-walled thermoplastic AM specimens.

2 Methodology

Due to the vast range of materials for AM, this study is limited to ABS materials. This offered the full range of thickness values, at a reasonable cost. Although higher quality materials are desirable for thin-walled sections, it is reasonable to apply a rationale to start with a standard base material, then consider expanding the choice of materials for later work. It is important to note the geometry of test specimens (fig. 1). The test specimens are based on ASTM D2990.

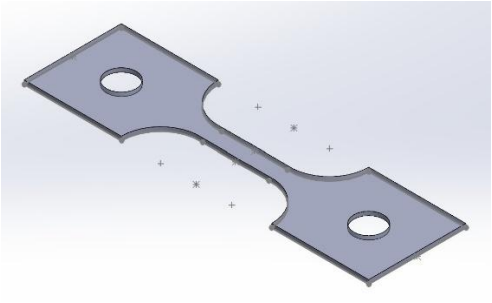


Fig.1 CAD file of the AM creep specimen.

Unlike thermosetting polymers, thermoplastics are more susceptible to creep deformation and failure. Viscoelasticity is a property that significantly influences the creep behaviour of thermoplastics [1] and it is important to study this in relation to the both the failure of thermoplastics in terms of creep deformation and creep rupture. The study selected two different in-fill styles, a basic form of rectilinear referred to as “sparse” by the manufacturer and hexagram. This allows a comparison of the weaker structures (recommended for prototyping rather than functional parts) and an improved, a more refined in-fill such as hexagram (fig. 2). The in-fill using a sparse construction allows a large variation of densities; commonly 15% is used however for this study it was needed to vary this. Densities of 20%, 30% and 40% were selected for the sparse in-fill. For the hexagram construction, the CAD software is limited for densities between 46% - 60%. Densities of 46%, 53% and 60% were selected. The pilot study used sample sizes of 15 for each type of in-fill at both temperatures.

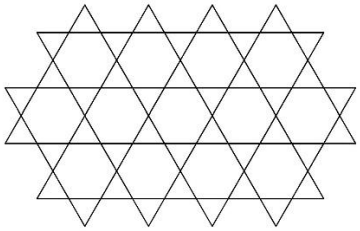


Fig. 2 Hexagram in-fill pattern.

Given the uncertainty of the creep behaviour, several specimens were tested under different loads to start with, which helped find a suitable loading amount for the study. The aim was to test them at ambient temperatures and an elevated temperature of 30°C. This was achieved by placing a mobile fan heater around 400 mm away from the specimen, heating the specimens prior to testing. Given the duration of full-testing, and that the initial recovery had to be observed, a timeframe was needed to show the secondary-state creep rate and allow the recovery to take place. The specimens were loaded for 20 minutes, then the weight removed. A nominal stress level of around 22 MPa was created by applying a 1.2 kg load to

the creep tester. Data from previous tensile testing revealed a tensile strength of 38 MPa for the AM ABS, based on ASTM D638 test specimens (using a rectilinear 15% in-fill). This is comparable to injection moulded specimens. As the creep specimens have a nominal thickness of 1 mm, the stress level needed to be high enough to promote the creep behaviour required for this study. Higher levels of stress resulted in many premature failures at ambient temperatures. Lower levels of stress exhibited low strain rates. The loading rate was determined experimentally. Prior to testing the specimens were weighed to look at variation in mass. Specimens were also measured across the gauge length (narrowest section) of the specimens. It was noted that the hexagram specimens were thicker than the sparse ones, with the sparse being on average 1.06 mm and the hexagram 1.12 – 1.17 mm. Widths also varied, with average values being used from each individually measured specimen prior to testing. The specimens were weighed prior to testing, with the average masses of the rectilinear specimens being 1.5037 g, 1.5133 g and 1.5605 g for the 20%, 30% and 40% in-fills respectively. The average masses for the hexagram specimens were 1.5181 g, 1.5208 g and 1.5258 g for the 46%, 53% and 60% in-fills respectively. The in-fill values are targets with a variation for the hexagram in-fill, which is dependent on the component geometry.

3.1.1 Experimental results

The elevated temperature testing at 30°C unsurprisingly resulted in mainly early creep ruptures (before the recovery phase after 20 minutes could be initiated) as well as the highest rates of secondary stage creep. Two thirds of the specimens ruptured. All specimens that showed secondary state creep rates of 3.4 x 10^{-6} s^{-1} survived until the 20-minute period and were then allowed to recover. The secondary state creep data however is not an indicator of survival for any given duration, as a few specimens did survive at much higher rates but in most cases rupture occurred. However, at very low secondary creep rates the expected survival of 20 minutes in this study is good. The combination in variation in material and defects from the AM process is a probable cause for some of the quickest ruptures. Most graphs plotted for the specimens which survived showed the expected creep curve (fig. 3) behaviour: initial deformation (due to instantaneous strain from loading) which was around 0.04 to 0.05 mm for most specimens, followed by a very short primary creep stage. Between 100 and 200 seconds most specimens enter the secondary state creep stage. With specimens exhibiting high secondary state creep rates, fracture was expected before the 20-minute time limit was applied.

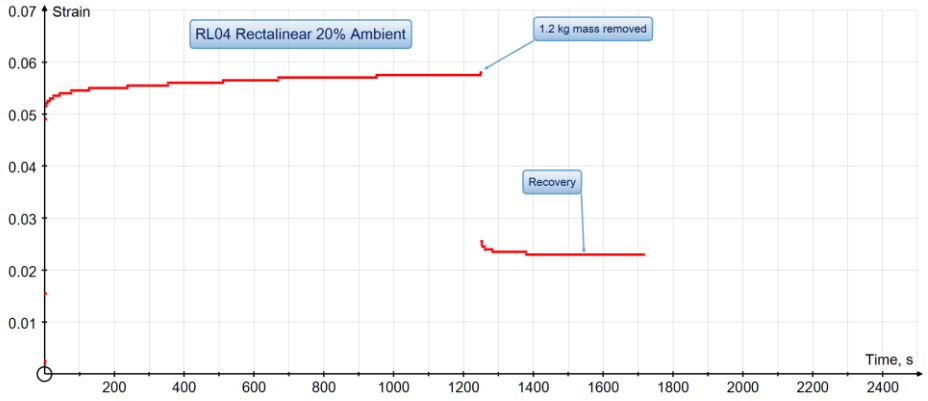


Fig. 3 Graph of a creep specimen (rectilinear with 20% in-fill) at ambient temperature.

A number of additional specimens were tested beyond the 20-minute loading period. These were left until rupture at ambient temperature. Their behaviour was very unpredictable

and clearly a much larger study would be needed to evaluate the creep-rupture characteristics at ambient temperature. For the specimens that showed low secondary state creep strain deformation, fracture occurred without any change in the strain rate. Others showed a higher rate of secondary state creep rate but lasted a few minutes longer than the creep specimens that were loaded for 20 minutes. Recovery was quite consistent for most specimens, with a modal value of 0.04 mm for the ambient specimens that survived. Three quarters of these recovered either 0.04 mm or 0.05 mm, which occurred over 5 minutes. Out of the few elevated temperature specimens that survived and recovered, the recovery in most cases was greater than the ambient, reaching up to 0.21 mm for one specimen. Much greater specimen batches are needed to evaluate this properly, and more work is needed at different temperatures. At elevated temperatures, fracture times were very short for most of the 20% and 30% rectilinear (fig. 4).

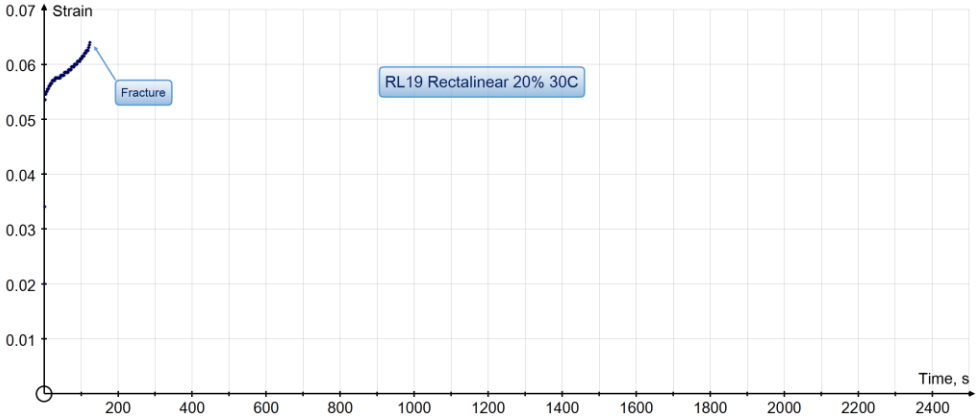


Fig. 4 Graph of a creep specimen (rectilinear with 20% in-fill) at 30°C.

The rapid rupture results that occurred with some of the rectilinear specimens at 30°C did not occur with the 46% and 53% hexagram specimens, although some did fracture, they entered a secondary-state creep stage for at least 10 minutes. The 60% hexagram specimens however fractured well within 10 minutes and performed poorly. Studies such as those by Gebrehiwot [2] have shown that in lot of cases, an increase in in-fill density does reduce the creep strain rate however the in-fill direction (for simple rectilinear) has a much bigger influence in many cases. to many models tested in other studies. What is apparent with the hexagram specimens is the reliability of the 53% in-fill at ambient temperature. These performed the better than any of the others and yet the 60% in-fill performed poorly at 30°C.

Another way to evaluate the specimens is by looking at the maximum strain achieved for ambient specimens. All the hexagram specimens and all the 40% rectilinear specimens had maximum strain values between 0.04 and 0.053, showing good consistency. Looking at these specimens, it is also evident that the most commonly occurring specimens with secondary-state creep rates between 1.5×10^{-6} s^{-1} and 2.5×10^{-6} s^{-1} are the 40% rectilinear and the 46% hexagram specimens. Whilst not fully conclusive, it does again show that the 60% hexagram are mainly absent from these ranges and supports the argument that the in-fill density alone does not always guarantee improved creep deformation properties. Another noticeable aspect from the testing is the level to which recovery can lead to; the hexagram in-fills showed less creep strain overall and the recovery region resulted in lower overall creep once the 5-minute recovery period had taken place (fig. 5).

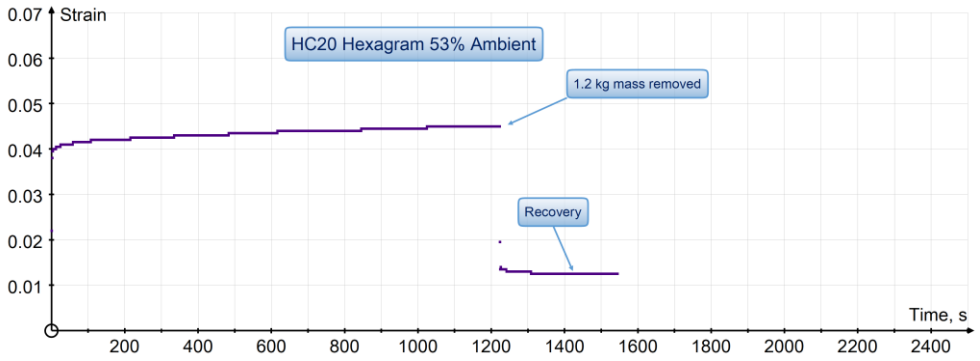


Fig. 5 Graph of a creep specimen (Hexagram with 53% in-fill) at ambient temperature.

One of the challenges for this testing was the need for constant manual monitoring of the temperature for the 30°C specimens. A better way to approach this is to utilise a temperature-controlled environment. Whilst a chamber is provided (shown in fig. 6, on the left-hand side), this is not temperature controlled and would have obstructed the fan heater. It had to be removed for the testing. The temperature probe was supported in-line with the specimen and constantly monitored throughout each test. The temperature variation across the specimen was not measured however given the small size of the specimen, and the operator-controlled variable distance to the fan heater (0.4 m), the specimen should not have over-heated or experienced a large variation in temperature. The testing was conducted during the early spring months in the UK, which helped ensure that solar gains were kept minimal. To help avoid any build-up of warm air in the laboratory, a conventional fan was used to gently circulate the air for the ambient testing of specimens. The study observed that there was a significant difference in the variations of temperature between the ambient and higher temperature specimens during the tests, which was expected, and confirmed using the Mann-Whitney U test ($p < 0.0001$). However, the relationship between premature failures at elevated temperatures and variation in temperature shows no correlation. This also is true for the strain rates and temperature variations (r values of less than ± 0.4 for rectilinear and hexagram in-fills for both temperatures). Temperature variation is multimodal when plotted for samples. Due to the skew present median values were recorded and variation in temperature recorded for each sample.

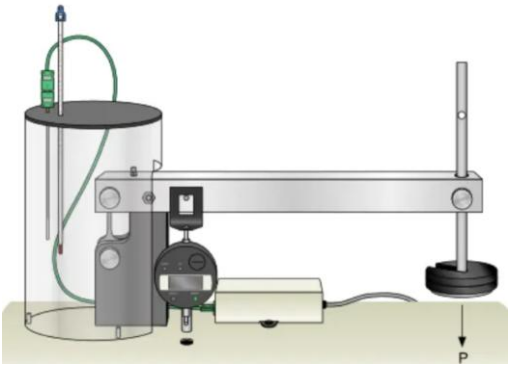


Fig. 6 Set-up of the experiment using the creep tester, with applied load, *P*.

3 Conclusions

This research has shown that the creep behaviour for ABS specimens can be analysed in a small study and give interesting results between ambient and elevated temperature environment conditions for different in-fills, which forms a basis for larger studies to be conducted. More work is needed to fully evaluate the creep behaviour of selected polymeric AM materials such as ABS, and future studies should incorporate other AM polymeric materials. The work has shown that whilst there is a high level of unpredictable behaviour at an elevated temperature of 30°C, ambient temperature testing benefits from larger in-fill densities for simple rectilinear in-fills. Using a more complex in-fill such as hexagram over rectilinear uses more material but does help reduce creep deformation and reduce the chances of premature creep rupture, however in this study it was found that the most suitable in-fill density is not the highest, but within the mid-range of the available in-fill densities (53%). There are a number of other studies [4, 5] which look at alternative in-fill structures that show improved mechanical properties for AM components, e.g. gyroid structures. These structures are studied for their influence on the tensile, compressive and flexural properties of AM parts [5] however there is scope to investigate their creep behaviour. Whilst solid in-fill hasn't been studied in this investigation, the purpose is to look at the creep behaviour for in-fill types that are common and present advantages over solid in-fill types. This study should be expanded for other materials, and in order to study the long-term creep behaviour, be conducted for longer periods. Different temperature studies (e.g. 25°C) would be beneficial to see how the polymers behave in between the elevated temperatures in this study and ambient temperatures. The authors propose that the research is continued, using larger sample sizes, different loading intervals and more temperature intervals in a temperature-controlled environment. Whilst other studies review the differences in mechanical properties of more complicated in-fill structures [4] over solid in-fills, there remains a lot of potential research for AM parts in terms of improving their creep resistance.

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