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Effect of Process Parameters on the Tensile Strength of Fused Deposition Modelling Parts

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ABSTRACT

Fused deposition modelling, the most common form of three-dimensional printing, builds a part by depositing molten plastic layer upon layer, and because the part is built up rather than cut from a solid block, its strength depends not only on the material but on how it is printed; the process parameters chosen, such as the thickness of the layers and how densely the interior is filled, strongly affect how strong the finished part is. This study examines the effect of process parameters on the tensile strength of fused deposition modelling parts, focusing on the layer thickness and the infill density. Test specimens were printed with different layer thicknesses and different infill densities, and their tensile strength, the force per unit area they could withstand before breaking when pulled, was measured and compared. The infill density had a strong effect: parts printed with a denser interior were considerably stronger, because more material carried the load, a fully filled part being substantially stronger than a half-filled one. The layer thickness also mattered: parts built from thinner layers were stronger than those built from thicker layers at the same infill, because thinner layers bond over a greater number of interfaces and give a more uniform structure. The strongest parts were therefore those printed with a high infill density and thin layers, though these also took longer to print and used more material, while the weakest were the thickly layered, sparsely filled parts that printed fastest. The study shows that the tensile strength of fused deposition modelling parts is governed substantially by the infill density and layer thickness, and it discusses the trade-off between strength and the time and material that printing consumes.

KEYWORDS: *Additive manufacturing, Fused deposition modelling, 3D printing, Tensile strength, Process parameters, Infill density, Layer thickness, Mechanical properties, Manufacturing*

INTRODUCTION

Additive manufacturing, widely known as three-dimensional printing, builds a part by adding material rather than removing it, depositing or solidifying material layer upon layer until the part is complete. This contrasts with traditional methods that cut a part from a solid block or form it in a mould, and it allows complex shapes to be made directly from a digital model, without tooling, which has made it valuable for prototypes, custom parts, and increasingly for functional components (1, 8). The most common and accessible form is fused deposition modelling, which builds a part by extruding molten plastic through a moving nozzle, laying down one thin layer at a time, each fusing to the one below as it cools (2).

Because a fused deposition part is built up from many layers rather than being solid throughout, its mechanical properties depend not only on the plastic used but strongly on how it is printed. The process parameters chosen for the print, among them the thickness of each layer, how densely the interior is filled with material, the orientation in which the part is built, and the speed and temperature of printing, affect the strength, stiffness, and quality of the finished part (3). A part may be printed quickly and with little material, or more slowly and solidly, and these choices change how strong it is.

Two parameters with a particularly strong influence are the layer thickness, how thick each deposited layer is, and the infill density, how much of the interior is filled with material rather than left hollow. This paper examines the effect of these process parameters on the tensile strength of fused deposition modelling parts, printing test specimens with different layer thicknesses and infill densities and measuring how strong they are. The aim is to show how the layer thickness and infill density govern the strength and to discuss the trade-off between strength and the time and material that printing consumes.

LITERATURE REVIEW

The mechanical properties of fused deposition modelling parts and their dependence on process parameters have been studied extensively, and the literature, reviewed comprehensively, relates the strength of printed parts to how they are made (5, 8). A consistent theme is that printed parts are not as strong as solid moulded ones and that their strength depends markedly

on the process parameters, so that choosing the parameters well is essential to producing strong parts (3).

PROCESS PARAMETERS AND STRENGTH

The literature describes how the process parameters affect the strength of printed parts:

- The infill density strongly affects strength, since more material in the interior carries more load (3).
- The layer thickness affects strength, thinner layers generally giving stronger, more uniform parts (6).
- Printed parts are anisotropic, being weaker across the layers than along them, owing to the bonds between layers (4).
- The fundamentals of the process and its parameters are set out in the standard references (1, 2, 7).

A recurring theme is that the strength of printed parts is governed substantially by the infill density and layer thickness, with a trade-off against printing time and material.

The literature reports that the infill density is among the most influential parameters for strength, denser parts being stronger because more material bears the load, and that the layer thickness also matters, thinner layers tending to give stronger and more uniform parts (3, 6). A further important finding is that printed parts are anisotropic, weaker across the layers than along them, because the bonds between successive layers are weaker than the material within a layer; this layered construction is central to understanding their strength (4). The optimization of these and other parameters, and the fundamentals of the process, are treated in reviews and standard references on additive manufacturing (1, 2, 7), with terminology and classification standardised in the relevant standard (10), and further optimization studies reported in the literature (9).

RESEARCH GAP

Although the effect of process parameters on the strength of printed parts is well studied, a concise demonstration that prints specimens at different layer thicknesses and infill densities, measures their tensile strength, and brings out the trade-off with printing cost remains useful as a clear illustration. There is therefore value in a study that shows how the strength depends on these two parameters together and relates it to the time and material printing consumes.

OBJECTIVES

The objectives of this study are:

- To print test specimens with different layer thicknesses and infill densities.
- To measure the tensile strength of each specimen.
- To compare the strength across the parameter combinations and identify the influence of each.
- To relate the strength to the printing time and material and discuss the trade-off.

METHODOLOGY

1. Specimens and Parameters

Test specimens for tensile testing were printed by fused deposition modelling with different combinations of two process parameters: the layer thickness, the thickness of each deposited layer, and the infill density, the proportion of the interior filled with material (3, 6). Their tensile strength, the force per unit area withstood before breaking when pulled, was measured. The parameters are summarised in Table 1.

Table 1: Process parameters and their levels

Parameter	Levels considered
Layer thickness	Thin to thick (mm)
Infill density	Low (sparse) and high (dense)
Material	Common thermoplastic filament
Response	Tensile strength of the printed specimen

2. Testing

The printed specimens were tested by pulling them until they broke and recording the tensile strength, and the strengths were compared across the layer thicknesses and infill densities to determine the influence of each parameter. The printing time and material used were also noted, so that the strength could be weighed against the cost of printing, and the parameter combination giving the strongest part identified (4, 5).

RESULTS AND FINDINGS

The infill density and layer thickness both strongly affected the tensile strength, as shown in Figure 1, which compares the strength of parts printed at different layer thicknesses and infill densities. The infill density had a strong effect: parts printed with a dense interior were considerably stronger than those printed sparsely, a fully filled part being substantially stronger than a half-filled one, because more material was present to carry the load (3).

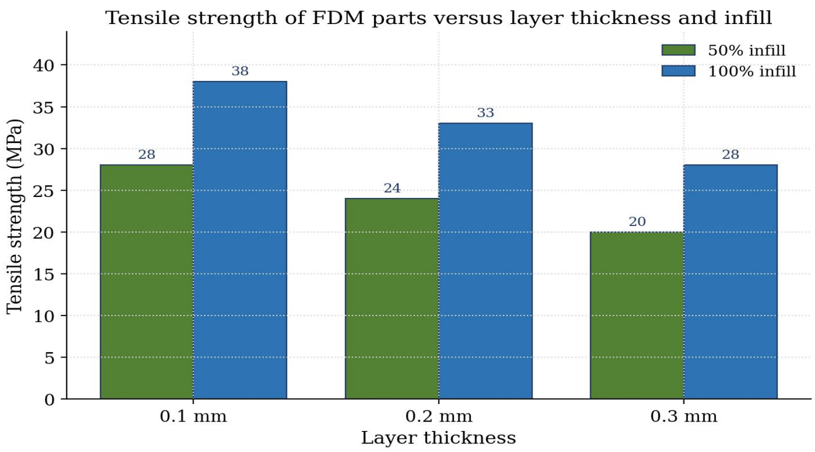

Figure 1: Tensile strength of FDM parts versus layer thickness and infill density

The layer thickness also mattered: at the same infill, parts built from thinner layers were stronger than those built from thicker layers, because thinner layers create more interfaces that bond together and give a more uniform structure, reducing the weakness between layers (4, 6). The strongest parts were therefore those printed with a high infill density and thin layers; but these took longer to print, since more layers and more material were deposited, and used more material, while the weakest parts, thickly layered and sparsely filled, printed fastest and used least. The results are summarised in Table 2.

Table 2: Effect of process parameters on tensile strength

Parameter	Effect on strength	Cost of stronger setting
Infill density	Higher density, stronger	More material, longer print
Layer thickness	Thinner layers, stronger	More layers, longer print

Parameter	Effect on strength	Cost of stronger setting
Strongest part	High infill, thin layers	Slowest, most material
Weakest part	Low infill, thick layers	Fastest, least material

DISCUSSION

The results show that the tensile strength of fused deposition modelling parts is governed substantially by the infill density and the layer thickness, and they have clear physical explanations. The strong effect of infill density is the most direct: the interior of a printed part need not be solid, and filling it more densely puts more material in the cross-section to carry a load, so a denser part is stronger almost in proportion to how much material it contains, while a sparsely filled part, mostly hollow, is correspondingly weaker (3). Infill density is therefore the first parameter to raise when a stronger part is needed.

The effect of layer thickness reflects the layered construction that distinguishes additive manufacturing. A fused deposition part is built from stacked layers, and the bonds between layers are weaker than the material within a layer, so these inter-layer bonds are where the part tends to fail (4). Thinner layers mean more, and better-fused, interfaces and a more uniform structure, which strengthens the part, whereas thicker layers mean fewer, coarser interfaces and a weaker, more anisotropic part (6). This is why thinner layers gave stronger parts, and it underlines that the strength of a printed part depends on how it is built, not only on the plastic used.

The practical significance is a trade-off between strength and the cost of printing, which governs the choice of parameters. The settings that give the strongest part, high infill density and thin layers, are also the slowest and most material-hungry, because they deposit more material in more layers, whereas the fastest, most economical settings, sparse infill and thick layers, give the weakest part (5). The parameters are therefore chosen according to what the part must do: a structural part that must bear load is printed densely with thin layers, accepting the longer print, while a prototype or lightly loaded part can be printed sparsely with thick layers to save time and material. The practical conclusion is that the infill density and layer thickness should be set to give the strength the part requires at the least cost in time and material, the main caveats being that the strength also depends on the material, the orientation, and other parameters, and that the results illustrate the trends rather than the strength of a specific part.

LIMITATIONS

The following limitations apply to this study:

- The strength also depends on the material, the build orientation, and other parameters not varied here.
- The results illustrate the trends rather than the strength of a specific part in service.
- Tensile strength was the property measured; stiffness, toughness, and fatigue were not assessed.
- Two parameters were varied; their interactions and the effect of others were not examined in detail.

FUTURE SCOPE

Future work could extend the present study as follows:

- Inclusion of build orientation and other parameters, such as printing temperature and speed.
- Measurement of further properties, including stiffness, toughness, and fatigue life.
- Comparison of different materials and their response to the process parameters.
- Optimization of the parameters jointly for strength, printing time, and material use.
- Assessment of the anisotropy of strength along and across the layers.

CONCLUSION

The effect of process parameters on the tensile strength of fused deposition modelling parts was examined by printing specimens with different layer thicknesses and infill densities and measuring their strength. The infill density had a strong effect, denser parts being considerably stronger because more material carried the load, and the layer thickness also mattered, thinner layers giving stronger, more uniform parts by improving the bonds between layers; the strongest parts were printed with high infill and thin layers, though these took longest and used most material. The study shows that the tensile strength of fused deposition modelling parts is governed substantially by the infill density and layer thickness, and that these should be chosen to give the required strength at the least cost in printing time and material, with the caveats that the strength also depends on the material, orientation, and other parameters and that the results illustrate the trends rather than the strength of a specific part.

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