Effect of the ironing process on parts produced by Fused Filament Fabrication

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Abstract
Fused Filament Fabrication (FFF) is an additive manufacturing process intended to build three-dimensional objects through selective deposition of melted material layer-by-layer along a pre-determined path. This technology is growing at an accelerated rate, being already widespread and used in many applications nowadays. As FFF becomes more important, its problems assume a bigger relevance. Warping is a distortion where the surfaces of the printed part do not follow the intended shape of the design and is one of the most common problems when printing in ABS.

Ironing, a heat treatment process present in the most recent FFF machines, has been proposed as a potential solution for this problem, however it is not clear at what degree is it actually a solution.

In order to meet this need, firstly this thesis aims to determine the influence of FFF printing parameters on the warping process of ABS. Secondly, a study on the impact of applying the ironing process on warped specimens aims to assess the viability of this solution.

Keywords: FFF, ABS, Warping, Printing parameters, Ironing.

1. Introduction
Additive Manufacturing (AM) assumes an indisputably important function in today's world. Cited by Forbes, Wohlers Report 2020 [1] states that expects: "(…) the revenue to climb to $23.9 billion in 2022, and $35.6 billion in 2024" [1].

Among the many different AM processes, the present work will focus on FFF, not only because this is one of the most used AM technologies, but also because the resources which are available at Instituto Superior Técnico (particularly at the Product Development Lab) proved to be suitable and useful for doing so.

AM comes with some disadvantages and internal cooling stresses is one of them. This phenomenon is very visible when the printed parts dimensions differ a lot from the expected, a theme that will be introduced further on, but that for the moment will be referred as 'warping'.

Warping (δ) is a distortion where the surfaces of the printed part do not follow the intended shape of the design. Warping is caused by residual stresses on the printed material that are generated during the cooling process. If the cooling process is not uniform, some regions of the part will be subjected to stress and possibly deform [2]. Curling is one of most usual manifestations of warping [3,4] formed by the different elongations and residual stresses in the part, leading to an upward bending [5].

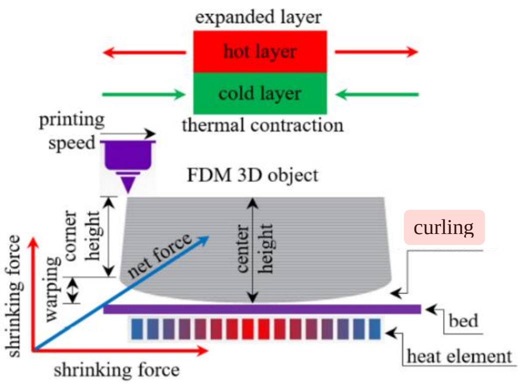

Figure 1 – Illustration of curling deformation, adapted from [6].

Curling usually takes place when the first layer does not stick well to the printing platform due to lack of adhesion [3] and it can be seen in Figure 1 that the curling effect particularly occurs in the component's edge regions. Given its importance for this study, from now on, the term 'warping' will be used abusively referring to the curling phenomenon.

Warping largely depends on the material, among other reasons, it increases with the thermal expansion coefficient and linearly increases with increasing material linear shrinkage rate [7], being less severe in Polylactic acid (PLA) than in ABS [2], as Figure 2 shows.

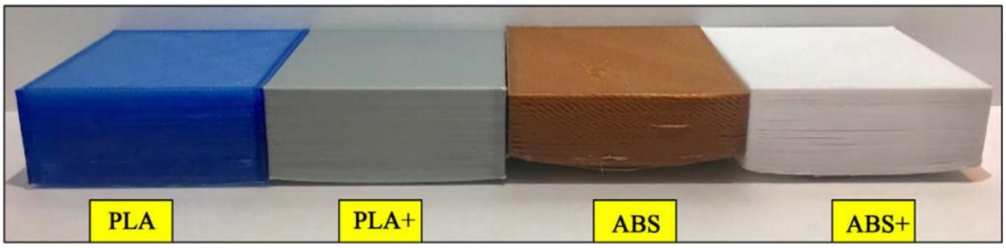

Figure 2 – Printed parts with different filament materials [8].

In fact, from the most used FFF materials, warping is only not visually neglectable on ABS [8–12] so that was the material chosen for this work.

In order to solve the warping problem on ABS, this study examined the performance of applying a heat treatment called 'ironing process', or just 'ironing' [2]. Ironing is a superficial treatment available on some slicing software which enables the heated nozzle to travel over printed layers with reduced or even no extrusion remelting the surface, as illustrated on Figure 3.

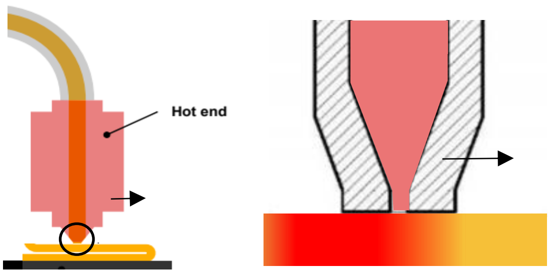

Figure 3 – Illustration of the ironing process.

2. Methodology

The methods used by the author share the focus of producing warping specimens consistently to then use the same printing conditions adding ironing layers across the part.

The ironing process, as all thermal processes, changes the properties of the printed part however that analysis is not the focus of this thesis, so no mechanical tests were experimented, rather the dimensions and overall looks of the part were considered. Both the ironed and non-ironed specimens were measured to infer the impact the treatment has on FFF printed parts.

2.1 Modeling

The CAD software used to model the specimen was *Solidworks 2019 (student version)* and the specimens were performed using a *Ultimaker S5* printer from Product Development Lab (LAB2ProD) at Instituto Superior Técnico.

The criteria used to select the best shape for the specimens included it having: enough surface area to remain stuck to the glass even when warped, a maximum height of 50 layers [7], a small volume to shorten printing time and multiple 90 degrees angles (corners) for the tensions to concentrate in those areas. Given these conditions and its use in the literature [2,6,13], a cuboid with 30x10x5 mm (Figure 4) was used for the tests.

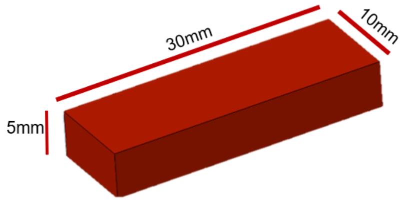

Figure 4 – Cuboid 30x10x5 mm illustration.

2.2 File processing

The slicing software used to edit all the printing parameters was *Ultimaker Cura 4.6*. Once the parameters were chosen, a g-code file was then created by the software and it served as input to a mid-processing software responsible for the ironing allocation parameters. This program was developed by Nuno Frutuoso for the BigFDM project [2], Nov2018, in Instituto Superior Técnico. Using the programming language Python, this software can find the ironing commands, only existent for the last layer, in the g-code and then replicate them to the layers chosen by the user. Consequently, it can only be used for parts with a constant shape across all layers, otherwise the ironing layer would be different from the previous printed layer.

Since there is almost no information about the impact of the ironing process on FFF specimens, three approaches were planned: applying ironing on the first layers, applying ironing evenly across the specimen, applying ironing consecutively on the first layers.

Regarding the second approach (applying ironing evenly across the specimen), the first layer to be ironed was only decided after the realization of the first tests. From those, the starting layer exhibiting the most warping should be the one chosen to be the starting layer for the equally spaced tests. For example, if ironing the 3rd layer presents the most warping compared with only ironing the 1st or the 2nd, then, all the equally spaced tests should start ironing on the 3rd layer. This way it is possible to better correlate the impact of spacing ironing across the part and the consequent warping reported.

2.3 Manufacturing

The number of printed parts per print may change the intensity of warping obtained since the time between layers would increase linearly with the number of parts. Given the almost inexistence information about the impact for the *ironing* process, it was decided that printing one part at a time would be the best way to ensure extrapolatable results.

‘Zero’ was the name given to the printed part with no ironing process applied. When referring to the term ‘zero’ it implies that the file used was always the same and in case the outcome of the part is different from one print to another then, it is due to external conditions (e.g. bed coating conditions). In the beginning of every series of prints, a zero was printed as a control specimen to ensure that the conditions were met. If the first zero presented visible warping (at least 10% of the specimen's height), then the series of tests with the ironing process could start, if not, the bed would have to be clean and another zero should be printed.

The material used for this work was *Ultimaker* ABS (Acrylonitrile Butadiene Styrene) red 2.85mm. ABS is particularly suitable for FFF since it is easily manageable in its pre-fusion state at low temperatures, steadily hardens as it cools down at glass transition temperature and reverts back to its initial properties [14].The objective was to choose a material that was very relevant to the industry, and which had a significant problem with warping. Moreover, this study comes in sequence from M. Sardinha [2] paper which also studied ABS.

2.4 Measuring

No mechanical tests will be performed, only the dimensions of the printed specimens will be compared. After printing the specimens, the author proceeded to measure them. The specimens were measured at the laboratory of *Tecnologias Oficinais* in *Instituto Superior Técnico.* The objective was to measure, as precisely as possible, the variations in the specimen's dimensions compared to the 3D CAD design. The specimen was measured in 6 different points, as Figure 5 illustrates, by an analog comparator.

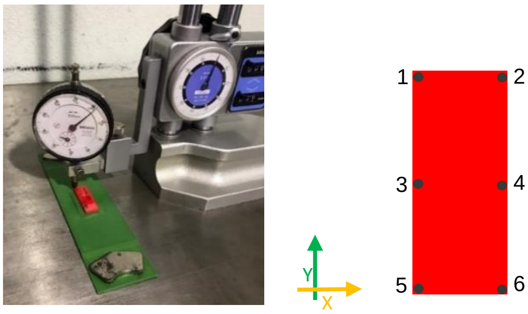

Figure 5 - Illustration of the measuring setup and points.

2.5 Results

Using the height measured by the analog comparator, the absolute and relative *warping* was calculated. The necessary formulas for this work can be found at Table 1.

Table 1 – Formulas to calculate warping.

Quantity	Symbol	Formula
Absolute warping	dw	$h - dz$ [mm]
Relative warping	w	$\frac{dw}{h} \times 100$ [%]
Average absolute warping	$\overline{dw_{5\&6}}$	$(dw_5 + dw_6)/2$ [mm]
Average relative warping	$\overline{w_{5\&6}}$	$(w_5 + w_6) \times 50$ [%]
Standard deviation	σ	$\sqrt{\frac{\sum(dw_i - \overline{dw_{5\&6}})^2}{n}}$ [mm]

3. Preliminary Tests

'Preliminary tests' was the name given to an initial group of prints performed to arrive at the most adequate parameters for the main tests. This analysis focused initially on the parameters that provided constant warping and secondly on the parameters that better suited the ironing process.

3.1 Achieving warping

From the very first tests performed, it was clear that the bed temperature had a great impact on warping. Therefore, a set of tests was conducted, to reach the temperature with the most consistent warping results. The bed temperatures tested were: No heat, 60ºC, 65ºC, 69ºC, 74ºC and 80ºC and the results can be seen on Figure 6 (1). Other than the bed temperature, bed coating also revealed to have a big impact on warping, therefore, three different surface coatings were tried: solid UHU glue, Isopropyl alcohol and glass cleaner. The results of these test are visible on Figure 6 (2).

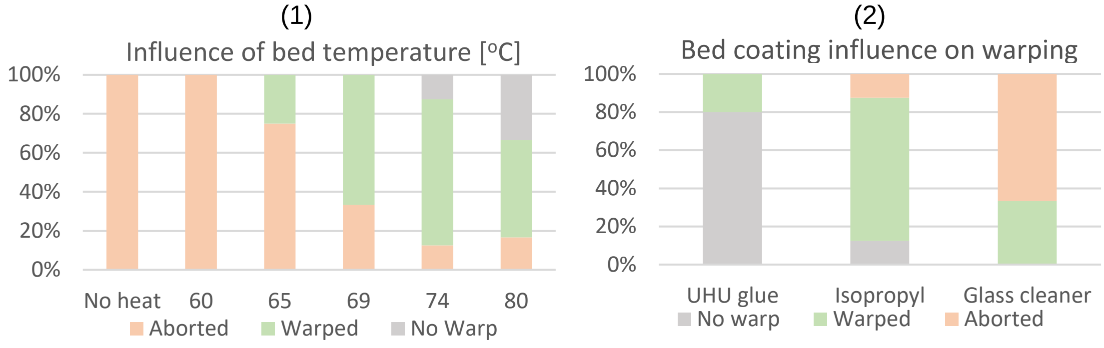

Figure 6 – Results of the (1) Bed Temperature and (2) Bed Coating tests.

The results from these tests were consistent with the literature: the bigger the bed temperature, the less likely it is for the part to warp. Since the author was looking for consistent warping results, the temperature of 74ºC and the Isopropyl coating were used on all further tests.

3.1 Implementing the ironing process

The bigger the printing temperature, the less warping expected [6] however, when trying to print at a temperature of 240 ºC and implementing ironing on various layers, visible on Figure 7 (2), the same draining problem reported by Sardinha M. [2], visible on Figure 7 (1), occurred. A series of tests, using a 10x10x10mm specimen and applying ironing every 5 layers, was then conducted to understand the optimal printing temperature. The results were ranked from 5 (very good condition) to 1 (poor condition) and they can be seen on Figure 7 (3).

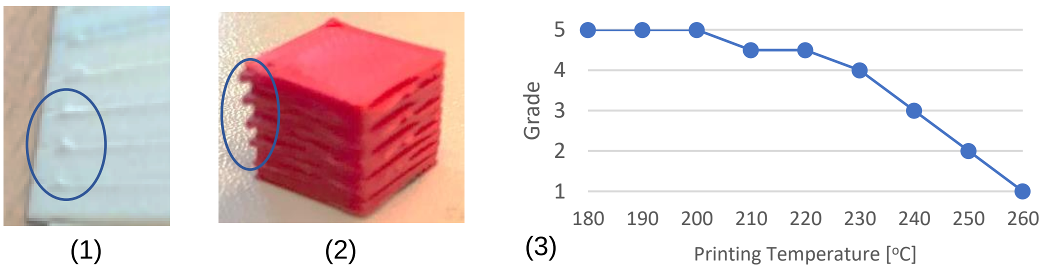

Figure 7 – Draining problem at (1) Sardinha [2] and (2) in this work. (3) Specimen's grading by Printing Temperature.

For temperatures below 210ºC, the nozzle temperature is not enough to melt/drain the leftover material on the tip; therefore, the finished part presents no visual deformations. However, such low printing temperatures lead to a not completely melting of the filament and the layer cohesion is compromised. For temperatures higher than 230ºC, unintended material extrudes for approximately 3 seconds, enough for the part to be compromised. The bigger the printing/ironing temperature, the bigger the 'draining' and the worse the final product. Literature suggests increasing the printing temperature to reduce warping at the same time it refers that it should not be lower than 215ºC for ABS [8,15]. Bearing in mind the attempt to conciliate a grading of 4.5 or 5 and getting the best out of interlayer cohesion, the printing temperature used for the tests was 220 ºC. Similar choices are found in the literature. [6,8,15]

4. Main tests and Discussion

The following list of prints/tests was conceived in accordance with the methodology explored in chapter 2, to analyze the impact of replicating ironing across other layers. As Table 2 shows, tests were divided in: non-ironed tests (highlighted in green), ironing on the first layers (highlighted in orange), equally spaced ironing (highlighted in yellow) and concentrated ironing (highlighted in blue).

Table 2 – List of tests and parameters

Tests	Ironing			General information					
N	interval	start	number of layers	coating	parts per print	spot	cleaning	#Zeros	#Ironed
(A1)	0	0	0	isopropyl	1	same	every print	4	0
(A2)	0	0	0	isopropyl	1	same	every print	4	0
(B1)	0	1	1	isopropyl	1	same	every print	1	4
(B2)	0	2	2	isopropyl	1	same	every print	1	4
(B3)	0	3	3	isopropyl	1	same	every print	1	4
(C1)	4	3	11	isopropyl	1	same	every print	1	4
(C2)	4	3	11	isopropyl	1	same	every print	1	4
(C3)	4	3	11	isopropyl	1	same	every print	3	3
(D1)	2	3	23	isopropyl	1	same	every print	1	4
(E1)	6	3	7	isopropyl	1	same	every print	1	4
(F1)	3rd to the 8th		6	isopropyl	1	same	every print	1	4
(G1)	1st to the 3rd		3	isopropyl	1	same	every print	1	4

On the non-ironed tests (A1) and (A2), the specimens were printed only using the fix parameters without applying any ironing. The absolute warping ($\overline{dw_{5\&6}}$) registered by these 2 series, varied from 0.736 to 0.866mm, a variation of only 2.6% of the total height of the specimen, which is impressive given the time gap between the different setups. As it can be seen on Figure 8, the zeros printed show consistent warping and with roughly the same intensity.

(A1) (A2)

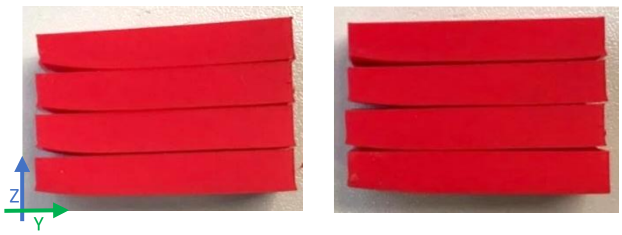

Figure 8 – (A1) and (A2) specimens.

From the results and the experience gathered from these tests, the author was confident that including only one non-ironed specimen for calibration in the ironed series of tests would be enough for accurate conclusions. Additionally, the value of the average standard deviation $\sigma_{5\&6} = 0.259mm$ is going to be used as the reference value for future comparisons.

The second tests performed included ironing only the first (B1), the second (B2) and the third layer (B3) of the specimen. As explained before, all the setups included an initial zero (shown in color blue) before performing the ironed tests and the results of it application can be seen on Table 3.

(1) (2)

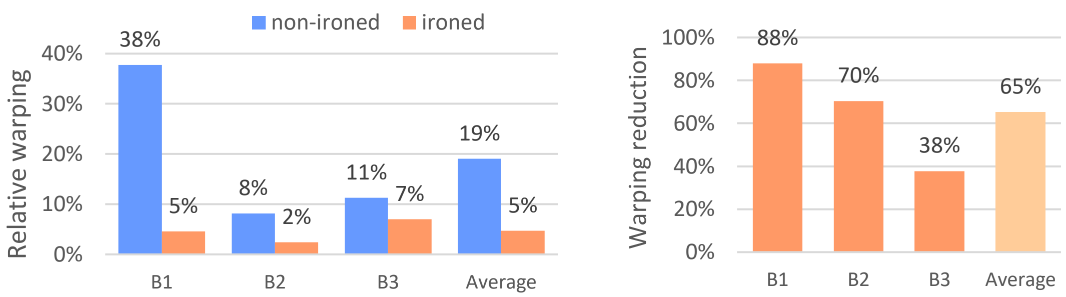

Table 3 – Comparison of the (1) Relative warping and (2) Warping reduction of the B specimens.

The results from the B series, revealed that, on average, the absolute warping reduced 75%, from 0.953 to 0.234mm. The highest warping reduction was achieved by ironing the first layer (B1 setup), followed by the second and the third (Table 3). The average standard deviation of

$\sigma_{5\&6}$ =0.220mm for the ironed B tests is higher than the $\sigma_{5\&6}$ =0.259mm of the non-ironed tests from A series, adding to the conviction that ironing the first layers of the specimen not only decreases warping but also reports more trustworthy results. These conclusions match with Sardinha M. (2020) [2] study which also stated that applying ironing on the first layers decreases warping.

Additionally, a characteristic present throughout the B series is, as Figure 9 shows, the presence of 'bed over-sticking' which led to the partial destruction of many specimens.

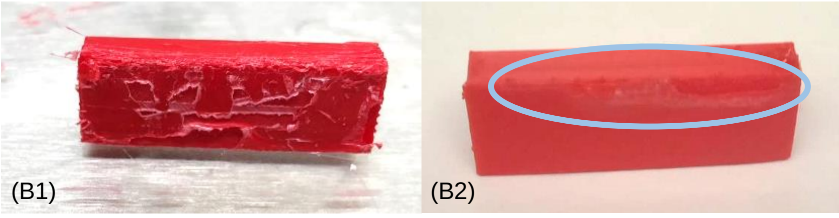

Figure 9 – Bed over-sticking effect on B1 and B2 specimens.

Understanding the impact of the ironing process inevitably required for the author to understand the effect of applying it across multiple layers of the specimen. The approach used included the application every two, four and six layers, corresponding to D, C and E setups respectively. From analyzing the data, the author decided not to consider the results from the C1 tests for further calculations and conclusions because, even though the results point in the same direction of the rest, this series indicates a systematic error given the so little warping effect compared with the others. Applying the ironing treatment across the specimen not only increased the time of printing but notably increased warping. All the performed tests exhibited on average more warping with than without the process, as illustrated on Figure 10 .

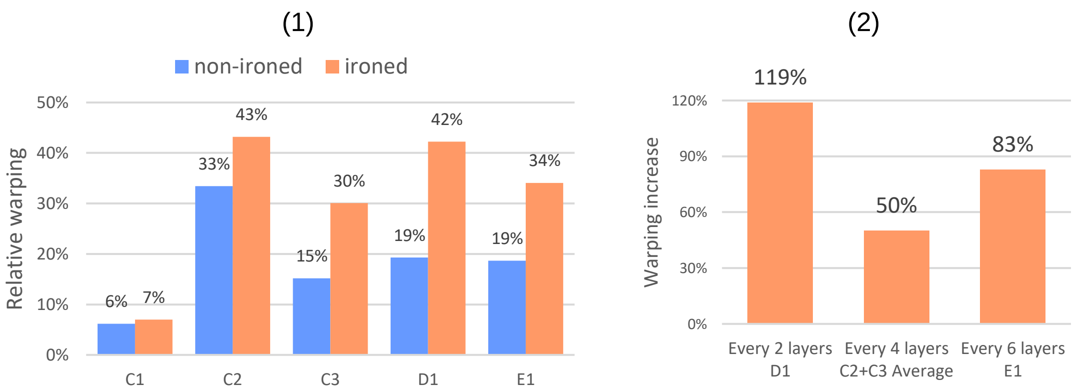

Figure 10 – Comparison of (1) Relative warping and (2) Warping reduction of the C, D and E specimens.

Ironing every 2 layers proved to be the worst solution so far, increasing the distortions on the specimen by 119%, followed by the application every 6 and 4 layers, reporting increases of 83 and 50% overall. As a result of these results, it seems that there is no advantage on ironing layers across the specimen. Applying this process so intensively increases the number of thermic cycles resulting in non-uniform thermal gradients causing internal stresses and leading to distortions/warping. The perception that spacing the ironing process across the specimen does not come as a viable solution for warping not only comes from the dimension results but also from the final looks of the specimen. Applying many layers of ironing, principally the ones with 2 and 4 layer interval, led to an excessive deposition of material, responsible for a partial destruction of the specimen (visible on Figure 12), certainly disabling the use of the part.

The fourth type of setup studied in this work involved applying the ironing process in consecutive layers. F1 tests applied the ironing process from the 4th to the 9th layer whereas G1 specimens from the 1st to the 3rd.

The results, visible on Figure 11 (1), show a clear difference on warping between the application of the ironing process until the 3rd layer (G1 specimens) and after the 3rd layer (F1 specimens). F1 specimens registered an increase of warping of 49% whereas G1 specimens registered a decrease of 79%, proving that there is no advantage on ironing the zone just after the 3rd layer of the specimen.

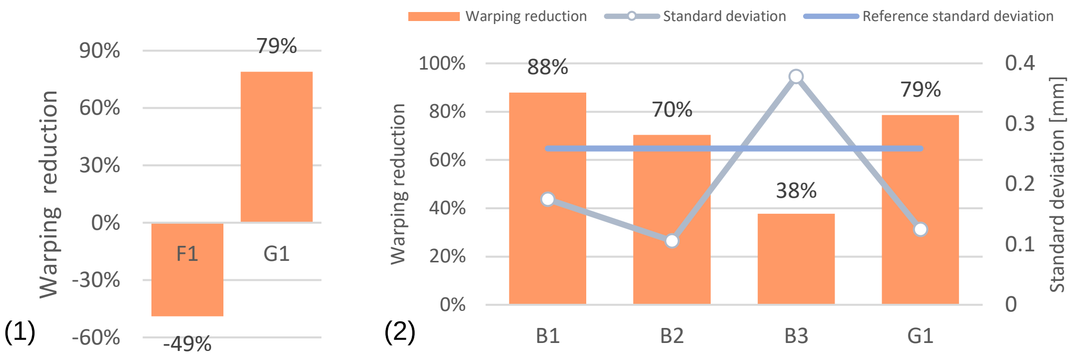

Figure 11 – Warping reduction on (1) F and G specimens and on (2) B and G specimens.

Given the inefficacy of results registered by F1, the most adequate comparison to make would be to compare the B setups with G1, explored on Figure 11 (2). In this case, G1 and B1 were the only tests analyzed so far that included the ironing process application on the first layer of the specimen and interestingly they both share bed over-sticking effect on 75% of its specimens and more than 75% warping reduction.

When looking to the aesthetics, the overall appearance, visible on Figure 12, changes a lot with the number and density of ironed layers.

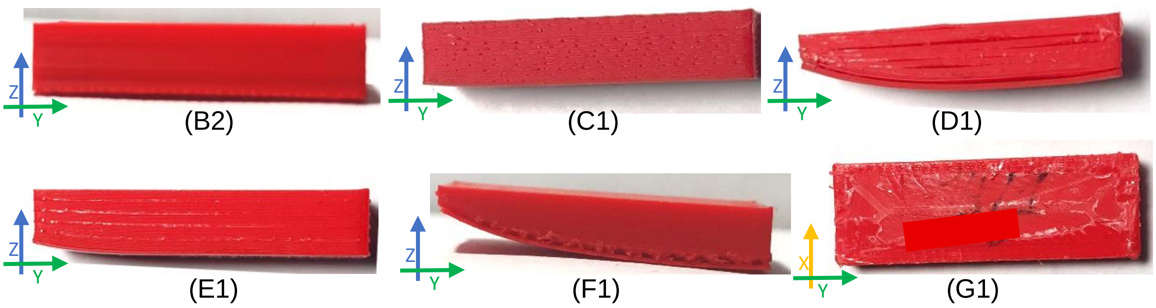

Figure 12 – Overall appearance of the ironed specimens.

As already mentioned, B specimens presented almost no signs of the ironing application, at least from a lateral appearance. The C specimens have some scraps, but nothing very noticeable. D specimens have visible stratified warping and separation between the layers. E specimens presented almost nonvisible signs of the process. The F specimens have their ironed layers melted and it is very visible on Figure 12. The G specimens presented the bed over-sticking effect and medium lateral distortions.

Applying the ironing process on a 30x10x5mm specimen increases the printing time by 2min and 42 seconds for each layer, adding to the non-ironed specimen of 38 minutes per part.

As an overall summary the author chose 4 main criteria: warping intensity, the lateral appearance, the bottom appearance, and the printing time and created a comparison table (Table 4) with all the results from this work. It was then assigned, to each setup and criteria, a score from 1 (very unsatisfactory) to 6 (optimized), based on each individual performance already elaborated in this chapter.

Table 4 - Final score comparation table.

	Warping	Lateral appearance	Bottom appearance	Printing time
A	3	6	6	6
B1	6	5	1	5
B2	5	5	2	5
B3	5	5	6	5
C	2	4	6	2
D	1	2	6	1
E	1	4	6	3
F	2	1	6	3
G	6	4	1	4

► Optimized

► Room for improvement

► Very unsatisfactory

5. Conclusions

Initially, the author tried to potentiate warping so that he could understand the impact of ironing. During that process it became very clear that there are already various parameters that could reduce warping, namely using the plate adhesion type “brim”, using high bed temperatures or applying glue or alcohol to the bed.

From the tests performed, specially when trying to understand the warping effect, the author concluded that, above all, the bed coating is the most determining factor on warping reduction. Another curious finding is that applying glue to the bed, as normally practiced on the 3D printing community, is not the most effective solution for its reduction, even more so when using high bed temperatures, rather applying hand sanitizer on the printing glass had substantially better results.

As proposed in the beginning, the first big conclusion of this work is that the author arrived at a set of parameters, conditions and specimen shape that successfully replicated warping indicating that this deformation can be tackled and controlled.

The second conclusion of this work is that ironing can, in fact, reduce warping, The ironing process applied throughout the specimen presents some advantages, namely the smoothness of the ironed layer and, in some cases, warping reduction, however it exhibits some drawbacks. Its application requires the user to know beforehand the most appropriate settings for an effective usage which may include using undesired printing settings on the rest of print just so that the ironing layer is performed correctly. Since the ironing process uses the same layer height and nozzle temperature as the other layers, it may force the user to choose a lower layer height and a lower printing temperature during all printing to make sure that the ironed layer is performed as intended. These changes could increase the printing time and fragilize the internal cohesion of the part. Even so, the improvement and widening of ironing process capabilities in the future, can be used to tackle the issue.

Another disadvantage of applying ironing to combat warping is the extra processing step, named ‘mid-processing’ in this work. Here, the g-code has to me modified to replicate the ironing layer across the part, adding at least 3 min of work to the user to be completed.

The author may conclude that the ironing process, as a solution for warping, at this time, is most adequate on parts that have a constant shape across the part, that would already use a layer height of 0.1mm or less and that would not be subjected to mechanical forces. Nevertheless, for these particular cases, this solution should only be considered if all the others failed to solve the problem. All these conditions may change if either the slicer or the mid-processing software update to newer version that included more detailed ironing parameters.

In case it is used, the best performing solution, in the author’s opinion, is only applying the ironing process on the third layer of the specimen. Even though it may depend on the objective, applying this ironing setup proved to reduce warping while it did not damage the first layer of the specimen, it did not show considerable signs of its application and it increased the printing time very residually.

Rather than being a finished project, this thesis can serve as a baseline for future work, namely to continue studying and understanding the characteristics of warping, understanding why does warping affect more one side than the other, testing these conclusions on other specimens and updating the mid-processing software so that it can include more degrees of freedom to the user.

The author visions that the actual panorama will evolve in the direction of the slicing software including a ‘Warping reduction’ option, as one of its parameters on the ‘Advanced settings’, with probably 2 levels of intensity (1) Soft and (2) High:

(1) The softest option would automatically iron the 3rd layer of the specimen.
(2) The more drastic option would automatically iron the 1st layer of the specimen.

Contrary to what the current software versions can do, both these options would require the software to correctly apply the ironing process on a specific layer of the specimen regardless of its shape. The software should at the same time try to avoid the draining problem. The author suggests for the program to automatically start lowering the nozzle temperature to 230ºC before the ironing layer or to effectively retract the filament just before ironing. Other solutions may surge as the knowledge and the technology improves being therefore essential further studies on the subject.

If the authors vision is implemented, this solution would potentiate the use of ABS to vaster applications since the fear of it warping would reduce substantially, and it would decrease the printing setup time, before and after the print, since it would reduce the need to apply and clean the bed coating (e.g. glue).

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