3D printing of spare parts: experimental study using non-standardized tests of the maximum supported torque

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Abstract: Industry 4.0 is scanning the spare parts of your machines and printing them directly when they are needed. This reduces storage space and shortens downtimes associated with corrective maintenance. In this work, we study which printing factors are the most important in spare parts that are going to be subjected to torque and have been manufactured by fused deposition modelling. For this purpose, an L16 design of experiments with three factors and two levels has been carried out. The factors studied were: number of shells, infill pattern and infill density. Following this design of experiments, cylindrical specimens with hexagonal heads were manufactured. These specimens were subjected to a non-standardized torsion test. From the experimental results, using the Taguchi method and the analysis of variance, it was found that the factors that most influence the maximum torque reached by the parts are the number of shells and the infill density. As a practical application of the work, the spare part for a water heater selector has been manufactured, using 5 shells and a density of 80 %.

Keywords: Additive manufacturing, Fused deposition modelling, 3d printing parts, Spare parts, Torsion test.

1. Introduction

Industry 4.0 is embracing additive manufacturing to produce spare parts when they are needed [1]. This reduces the size and cost associated with spare parts warehouses and shortens downtime associated with corrective maintenance [2].

FDM technology is one of the most widely used in the manufacture of spare parts, due to several factors [3,4]: it is the most affordable, it allows the printing of large format parts, it allows the extrusion of materials with different properties (mechanical, magnetic, food contact, resistance to ultraviolet rays).

One of the most widely used materials in the manufacture of spare parts using FDM is ABS. Although it is more difficult to print than other materials, ABS has several advantages [5]: excellent mechanical properties compared to other thermoplastics, working temperature up to 100 °C, excellent surface finish can be achieved by chemical polishing, it can be sanded.

The mechanical properties of FDM printed ABS parts are well known. There are numerous works in the literature that have determined by tensile tests the tensile strength and the elastic modulus for different parameters and printing positions [6]. There are also works that study the properties of parts when they are subjected to bending tests. Less frequent are authors who have studied the behavior of
parts subjected to torsion [7]. This work is very interesting, as it compares the mechanical properties with respect to torsion in parts manufactured by injection molding and 3D printing.

The aim of this work is to study the torsional behavior of printed parts as a function of different printing parameters (number of shells, infill pattern and infill density). For this purpose, a design of experiments L16 has been developed and a Taguchi and ANOVA analysis has been carried out on the results obtained by means of non-standardized torsion tests. The parameters studied were: number of shells, infill pattern and infill density. No previous work has been found where the influence of these parameters on the torsional behavior of 3D printed parts has been studied. This is one of the main contributions of this work.

2. Methodology

The methodology used in this work was as follows: (i) elaboration of a design of experiments (DOE); (ii) 3D design of the specimens; (iii) printing of the specimens, following the DOE; (iv) performing the torsion tests on the specimens; (v) processing the data and obtaining results.

To develop the design of experiments, the following input variables were chosen: number of shells, infill pattern, and infill density. After sensitivity tests, two values were set for each variable (table 1). From these values, using an arrangement of 16 experiments, the different combinations shown in table 2 were generated.

The specimens were designed using SolidWorks (SW) software (version 2018). The geometry and dimensions of these can be seen in figure 1. The file generated by SW in STL format (stereolithography) was imported from FlashPrint (version 4.4.0), where the printing parameters were selected following the DOE previously elaborated. The G-code files generated by FlashPrint were sent to the Flashforge Creator Pro 3D printer. ABS filament, supplied by Smart Materials 3D, was used to print the specimens. In addition to the values indicated in DOE for each specimen, the following printing parameters were used: layer height equal to 0.2 mm, printing speed equal to 60 mm/s, extrusion temperature equal to 220 ºC and bed temperature equal to 105 ºC.

![Figure 1. Geometry of the specimen used in the tests.](image)

The specimens were broken using a set up as shown in figure 2. Each specimen was fixed to a bolt installed on a workshop table; using an ACDelco model ARM601-4 ½” audit torque wrench, the specimen was subjected to a torque. The maximum torque value, reached at the moment of breakage, is recorded by the wrench and displayed on its digital display. This test, although not standardized, allows
the torsional behavior of a real part to be studied. Previous studies have used torque wrench to analyze the mechanical behavior of 3D printed parts [8].

The values obtained were analyzed using the Taguchi method and analysis of variance (ANOVA) [9]. Once the tests were completed, a part was designed that can serve as a spare part for a water heater knob.

### Table 1. Parameters included in the study and values selected for each level.

|                  | -1  | +1  |
|------------------|-----|-----|
| Number of shells | 3   | 5   |
| Filling Pattern  | hexagonal | triangular |
| Filling Density (%) | 60   | 80   |

### Table 2. Design of experiments L16 and non-standardized torque test results.

| Number of shells | Filling Pattern | Filling Density (%) | Maximum Torque (Nm) |
|------------------|-----------------|--------------------|--------------------|
| 1                | 3               | Hexagonal          | 60                 | 42.8               |
| 2                | 5               | Hexagonal          | 60                 | 57.4               |
| 3                | 3               | Triangular         | 60                 | 48.4               |
| 4                | 5               | Triangular         | 60                 | 56.2               |
| 5                | 3               | Hexagonal          | 80                 | 63.2               |
| 6                | 5               | Hexagonal          | 80                 | 48.6               |
| 7                | 3               | Triangular         | 80                 | 55.9               |
| 8                | 5               | Triangular         | 80                 | 61.6               |
| 9                | 3               | Hexagonal          | 60                 | 45.2               |
| 10               | 5               | Hexagonal          | 60                 | 50.6               |
| 11               | 3               | Triangular         | 60                 | 48.4               |
| 12               | 5               | Triangular         | 60                 | 56.2               |
| 13               | 3               | Hexagonal          | 80                 | 57.1               |
| 14               | 5               | Hexagonal          | 80                 | 58.4               |
| 15               | 3               | Triangular         | 80                 | 56.0               |
| 16               | 5               | Triangular         | 80                 | 60.5               |

### 3. Results

The cylindrical specimens were subjected to a torsion test (figure 2). Despite not being a standardized test, the values obtained for the maximum supported torque for identical specimens are very similar (figure 3). Figure 4 shows the initial and final state of one of the specimens before and after the test. The maximum torque values obtained for each of the specimens can be found in the last column of table 2. As can be seen, the maximum torque values range from 42.8 N · m (specimen 1) to 63.2 N · m (specimen 5).

These values were processed using the Taguchi method and analysis of variance (ANOVA). The results obtained are shown in figure 5 and table 3, respectively. As can be seen from the mean of means graph (figure 5), there is a relationship between the printing factors studied and the maximum torque achieved by the specimens in the tests. From figure 5, it can be stated that a specimen manufactured with a higher number of shells, a triangular infill pattern and a higher infill density is the one that would achieve the highest maximum torque. According to the ANOVA (table 3), the most influential factor is the infill density (p-value < 0.05), followed by the number of shells (p-value ≤ 0.10).
Figure 2. Non-standardized torque test to measure experimentally the maximum torque supported by the part.

Figure 3. Maximum torque values obtained in the different tests.

Once the study described above had been carried out, a selector knob for a water heater was manufactured (figure 6). As can be seen, the replacement part has a geometry like that of the test specimens tested. The combination of factors used for its manufacture was as follows: number of shells equal to 5; triangular infill pattern; infill density equal to 80 %. According to the tests (table 2), this selector would be able to transmit a maximum torque equal to $60 \text{ N} \cdot \text{m}$.

Figure 4. State of the specimen before (left) and after (right) the non-standard torsion test.
**Figure 5.** Main effects plot for means.

**Figure 6.** 3D model of water heater knob (left and center); 3D printed knob using the printing parameters obtained in the tests.

**Table 3.** ANOVA results.

| Source               | Degrees of Freedom | Sum of Squares | Contribution (%) | Mean Square | F value | p-value |
|----------------------|--------------------|----------------|------------------|-------------|---------|---------|
| Number of shells     | 1                  | 66.02          | 12.04            | 66.02       | 3.04    | 0.107   |
| Filling Pattern      | 1                  | 24.75          | 4.51             | 24.75       | 1.14    | 0.307   |
| Filling Density      | 1                  | 196.70         | 35.87            | 196.70      | 9.05    | 0.011   |
| Lack of adjustment   | 4                  | 167.70         | 30.58            | 41.92       | 3.60    | 0.058   |
| Pure error           | 8                  | 93.23          | 17.00            | 11.65       |         |         |
| Total                | 15                 | 548.40         | 100.00           |             |         |         |

4. Conclusions

We are observing a paradigm change in maintenance departments. In many companies, these departments now have fused filament deposition modelling printers and skilled additive manufacturing technicians. Companies realize that it is more efficient to manufacture spare parts in a few hours rather than having to wait several days for spare parts to be shipped from halfway around the world.
This work focuses on the study of spare parts that are subjected to torque. Specifically, the aim is to find out which factor (number of shells, infill pattern, infill density) is the most influential on the maximum torque that the part can transmit. For this purpose, cylindrical specimens with hexagonal heads have been designed and printed following a design of experiments. The specimens were subjected to a non-standardized test to determine the maximum torque transmitted.

Via ANOVA, it was found that the most influential factors on the maximum torque supported by the specimens are the infill density (p < 0.05) and the number of shells (p ≤ 0.10). Using an infill density of 80 %, a number of shells equal to 5, and a triangular infill pattern, a maximum torque equal to 60 N·m can be achieved.

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