A Theoretical-Experimental Study of the Influence of FDM Parameters on PLA Spur Gear Stiffness

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Abstract-This paper studies the influence of FDM (Fused Depositing Modeling) parameters on gear stiffness made of Polylactic Acid (PLA). 3D printing parameters must be optimized because they influence the physical, mechanical, and quality characteristics of the additive manufactured part along with its functionality. The objective of this research is to optimize FDM parameters in order to obtain the highest stiffness. In this context, we used Finite Element Analysis (FEA) and we made experimental tests to validate its results. The experimental tests are divided into two categories, gears with the same parameters and gears with the same layer height and variable filling percentage. The average results of gear stiffness with the same parameters are 8.18% highest than the average results of gear stiffness with the same layer height and variable filling percentages.

Keywords–3D printing; FDM parameters*; *FDM parameters; stiffness; spur gears; FEA

I. INTRODUCTION

The term additive manufacturing encompasses a set of technologies and processes that use different materials to make objects by depositing material in successive layers. Due to the recent improvements in additive technologies, they are used in many fields of activity. Initially, they were suitable for rapid prototyping of models, now they are used for sophisticated applications such as unique parts, custom products, medical implants, etc. [1-4]. Compared to formative and subtractive manufacturing, additive manufacturing technologies have many advantages: material waste is negligible, realization of very complex objects without bases and fasteners, cost-effective manufacturing, simplicity in use, etc. [5, 6]. In this paper we show that FDM 3D printing with PLA can be a good solution for plastic gears and we also find the optimal parameters for FDM printed gears. The novelty of this article consists in determining the influence of FDM parameters, the height of the deposited PLA layer, and the percentage of filling for spur gears with straight teeth, on the rigidity gear assembly. The rigidity of PLA gear assembly, 3D-printed by FDM, is theoretically determined using FEA and experimentally validated using a device designed and manufactured by the authors, whereas the recording of the results was realized by a digital torque wrench [7, 9].

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II. FDM 3D PRINTING OF SPUR GEARS

PLA filament with a diameter of 1.75mm, Verbatim brand, was the material used for FDM 3D printing of the spur gears with straight teeth. The printing methodology is shown in Figure 1.

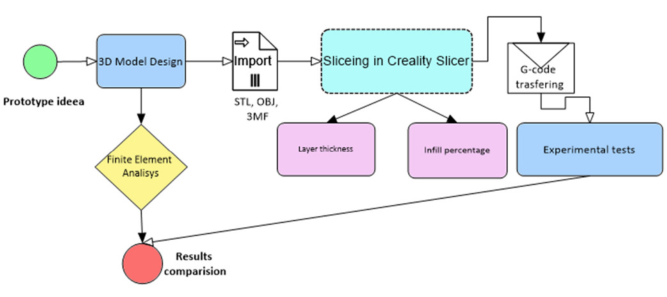


Fig. 1. Study methodology.

2D and later 3D models of straight-tooth cylindrical gears were made in the CAD Solidworks program. Figure 2 shows the 2D model of the drive gear module 1 with 30 straight teeths (R1) and Figure 3 shows the 2D model of the drive wheel module 1 with 60 straight teeth (R2). Both were designed in Solidworks. Using the same software, the two CAD files corresponding to the 3D models obtained were saved with the STL extension.

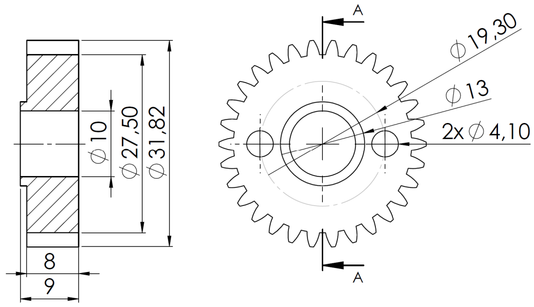


Fig. 2. Leading spur gear (R1).

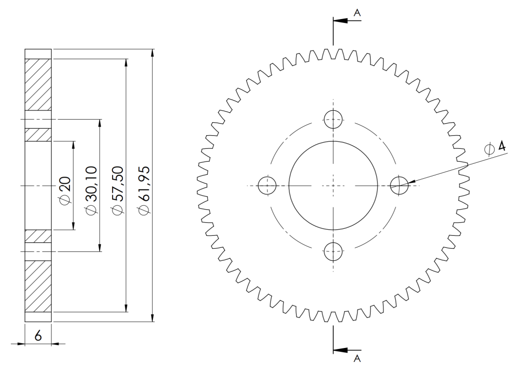
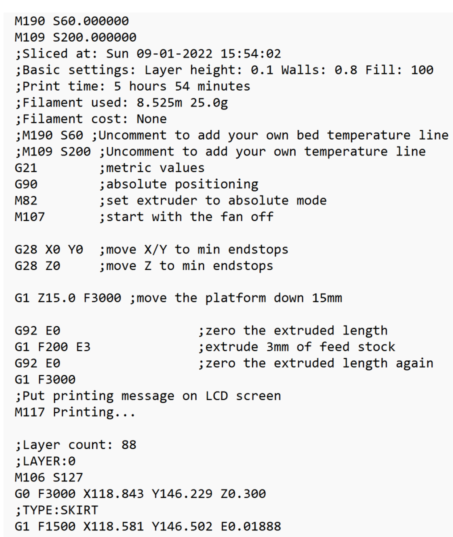


Fig. 3. Driven spur gear (R2).

Using the Creality Slicer program of the Creality CR-X printer, the two files with the STL extension corresponding to the straight-tooth cylindrical gears shown in Figures 2 and 3, after entering the 3D printing parameters, were transformed into a G-file Code (Figure 4).



```
M190 S60.000000
M109 S200.000000
;Sliced at: Sun 09-01-2022 15:54:02
;Basic settings: Layer height: 0.1 Walls: 0.8 Fill: 100
;Print time: 5 hours 54 minutes
;Filament used: 8.525m 25.0g
;Filament cost: None
;M190 S60 ;Uncomment to add your own bed temperature line
;M109 S200 ;Uncomment to add your own temperature line
G21        ;metric values
G90        ;absolute positioning
M82        ;set extruder to absolute mode
M107       ;start with the fan off

G28 X0 Y0  ;move X/Y to min endstops
G28 Z0     ;move Z to min endstops

G1 Z15.0 F3000 ;move the platform down 15mm

G92 E0                  ;zero the extruded length
G1 F200 E3              ;extrude 3mm of feed stock
G92 E0                  ;zero the extruded length again
G1 F3000
;Put printing message on LCD screen
M117 Printing...

;Layer count: 88
;LAYER:0
M106 S127
G0 F3000 X118.843 Y146.229 Z0.300
;TYPE:SKIRT
G1 F1500 X118.581 Y146.502 E0.01888
G1 X118.362 Y146.826 E0.03839
```

Fig. 4. G-Code commands.

The parameters of 3D printing of cylindrical gears, presented in Table I, are grouped in two categories, constant process parameters and variable technological parameters. The first parameters category refers to the orientation of the parts, the printing speed (V_p), the extruder temperature (T_e), the printing bed temperature (T_p), and the model used for filling. Variable technological parameters refer to the height of the deposited layer (H_s) and the percentage of filling, (P_u) [1]. Also, the number of gear pairs tested is mentioned. Data in Table I were used to reveal constant parameters and parameters varied to test different layer thicknesses and infill percentages.

TABLE I. 3D PRINTING PARAMETERS

<table>
<tr><th>Constant parameters</th><th colspan="4">Variable parameters</th><th colspan="2">Spur gears</th></tr>
<tr><td rowspan="2">Building orientation
X, Y</td><td>Layer hight (H_s)</td><td colspan="3">Infill percentage (P_u)</td><td>R1</td><td>R2</td></tr>
<tr><td>(mm)</td><td colspan="3">(%)</td><td colspan="2">(pieces)</td></tr>
<tr><td rowspan="2">Extrusion temperature (T_e) – 210 °C</td><td>0.10</td><td rowspan="3">50</td><td rowspan="3">75</td><td rowspan="3">100</td><td colspan="2">27</td></tr>
<tr><td>0.15</td><td colspan="2">27</td></tr>
<tr><td>Bed temperature (T_p) – 60 °C

Speed (V_p) – 80 mm/s

Filling model – Lines 45°</td><td>0.20</td><td colspan="2">27</td></tr>
</table>

Figure 5 shows the set of cylindrical gears with straight teeth R1 and R2, created with the Creality Slicer [3]. The G-Code file was transferred to the Creality CR-X printer on which 162 straight-tooth cylindrical gears were made of PLA (81 R1 and 81 R2), according to the data centralized in Table I.

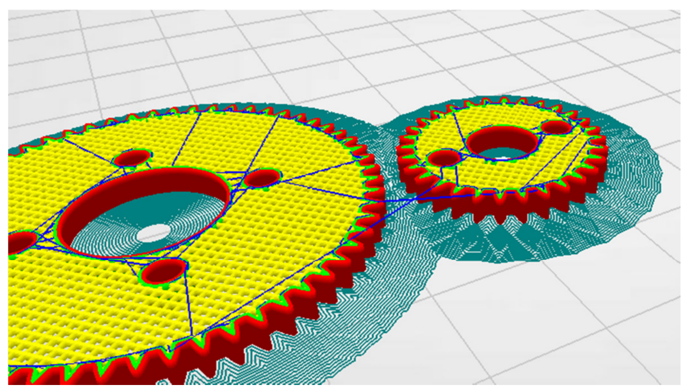


Fig. 5. R1 and R2 spur gears, in Creality Slicer.

III. STIFFNESS DETERMINATION OF THE 3D PRINTED SPUR GEAR

The stiffness of the PLA 3D printed spur gears was theoretically determined using FEA applied in Solidworks 2016 and experimentally validated using the device in Figure 8 designed and manufactured by the authors.

A. *Theorethical Study*

For FEA of stiffness gears with straight in Solidworks 2016 a torque R1 equal to 0.0022kN·m was applied (minimum value at which teeth yielded). The FEA results of the stiffness of the straight-tooth cylindrical gears of PLA (R1 and R2) are shown in Figures 5 and 6. The equivalent Von Mises stress obtained is 2.225MPa and the maximum linear displacement is 1.208mm.

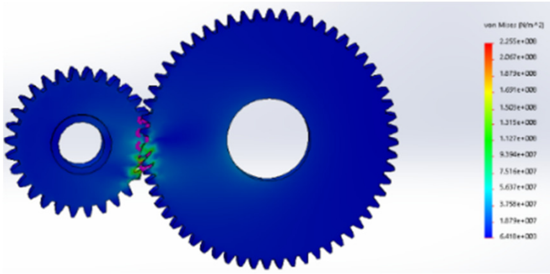


Fig. 6. Equivalent Von Mises stress.

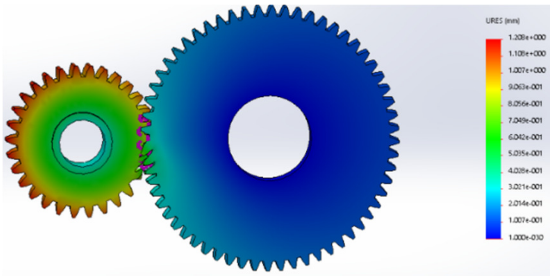


Fig. 7. Maximum linear displacement.

B. *Experimental Tests*

For the experimental determination of the gear stiffness of the gears, the authors designed and made the device shown in Figure 8.

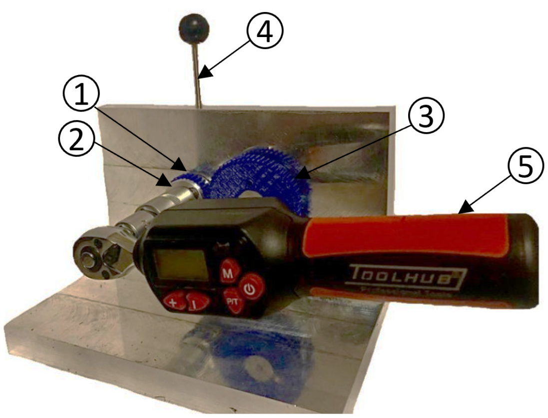


Fig. 8. Gear stiffness determination device: 1 – leading gear (R1); 2 – washer; 3 – driven wheel (R2); 4– locking rod; 5 – digital torque wrench.

The stiffness of the leading gear R1 (1), fixed to the device by the washer (2) and locked by the rod (4), with the driven gear R2 (3) was determined by the digital torque wrench (5) by recording the maximum torque corresponding to the gear assembly failure. A total of 162 experimental tests were performed on the device in Figure 8, using cylindrical gears with straight teeth with the parameters shown in Table I.

C. *Results and Discussion*

The results obtained from the experimental determinations performed on the device in Figure 8 are shown graphically in Figures 9-36. The averages of the results obtained from the experimental determinations; are presented in Figure 36.

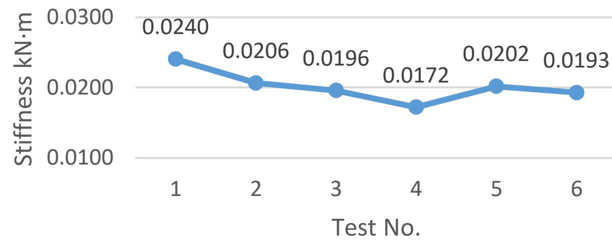


Fig. 9. Gear stiffness R1 (H_s = 0.10mm, P_u = 100%) with R2 (H_s = 0.10mm, P_u = 100%).

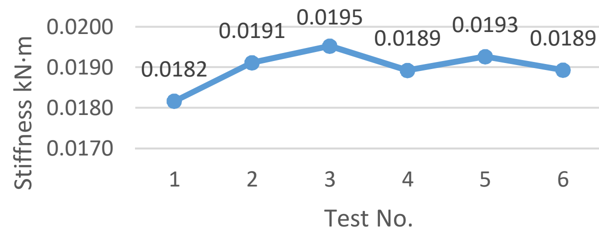


Fig. 10. Gear stiffness R1 (H_s = 0.10mm, P_u = 75%) with R2 (H_s = 0.10mm, P_u = 75%).

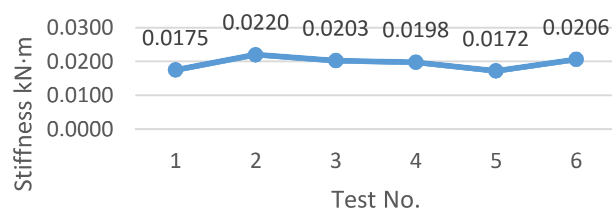


Fig. 11. Gear stiffness R1 (Hs = 0.10mm, Pu = 50%) with R2 (Hs = 0.10.mm, Pu = 50%).

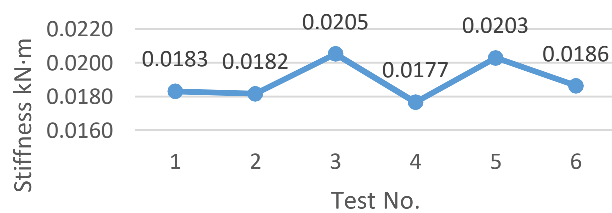


Fig. 12. Gear stiffness R1 (Hs = 0.15mm, Pu = 100%) with R2 (Hs = 0.15mm, Pu = 100%).

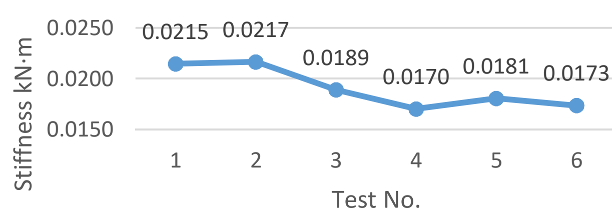


Fig. 13. Gear stiffness R1 (Hs = 0.15mm, Pu = 75%) with R2 (Hs = 0.15mm, Pu = 75%).

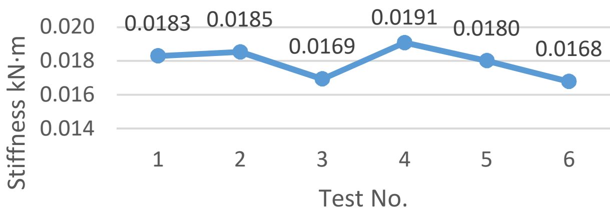


Fig. 14. Gear stiffness R1 (Hs = 0.15mm, Pu = 50%) with R2 (Hs = 0.15mm, Pu = 50%).

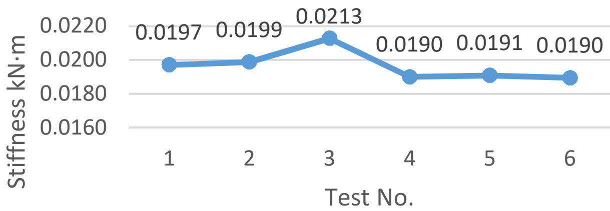


Fig. 15. Gear stiffness R1 (Hs = 0.20mm, Pu = 100%) with R2 (Hs = 0.20mm, Pu = 100%).

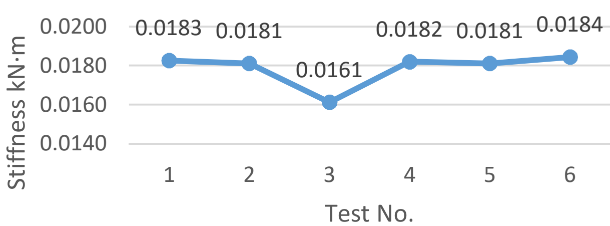


Fig. 16. Gear stiffness R1 (Hs = 0.20mm, Pu = 75%) with R2 (Hs = 0.20mm, Pu = 75%).

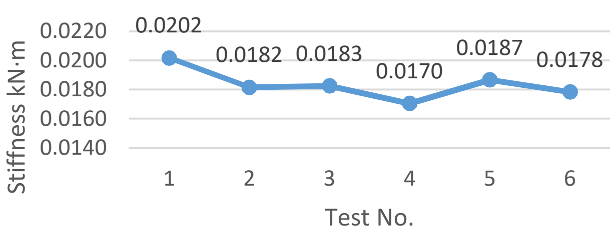


Fig. 17. Gear stiffness R1 (Hs = 0.20mm, Pu = 50%) with R2 (Hs = 0.20mm, Pu = 50%).

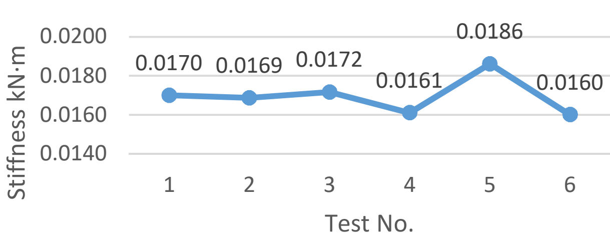


Fig. 18. Gear stiffness R1 (Hs = 0.10mm, Pu = 100%) with R2 (Hs = 0.10mm, Pu = 75%).

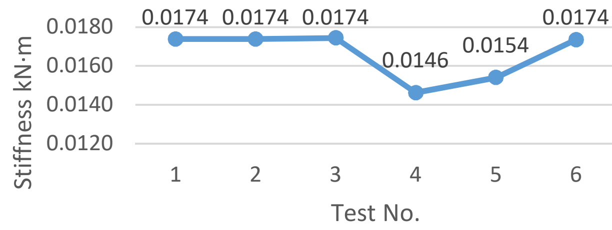


Fig. 19. Gear stiffness *R*1 (Hs = 0.10mm, Pu = 100%) with *R*2 (Hs = 0.10mm, Pu = 50%).

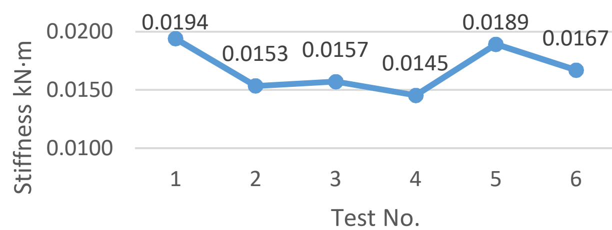


Fig. 20. Gear stiffness *R*1 (Hs = 0.10mm, Gu = 75%) with *R*2 (Hs = 0.10mm, Pu = 100%).

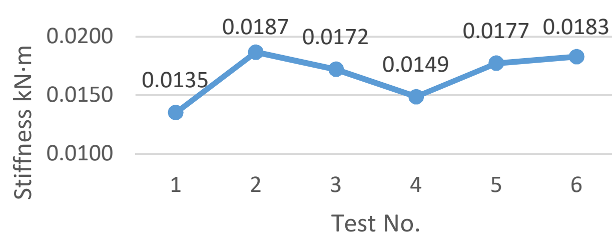


Fig. 21. Gear stiffness *R*1 (Hs = 0.10mm, Pu = 75%) with *R*2 (Hs = 0.10mm, Pu = 50%).

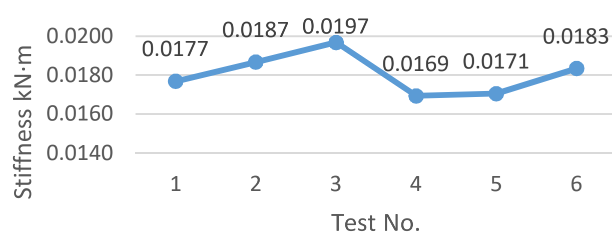


Fig. 22. Gear stiffness R1 (Hs = 0.10mm, Pu = 50%) with R2 (Hs = 0.10mm, Pu = 100%).

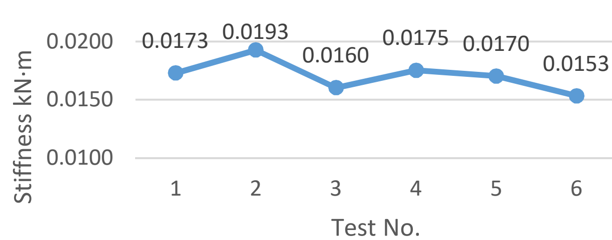


Fig. 23. Gear stiffness *R*1 (Hs = 0.10mm, Pu = 50%) with *R*2 (Hs = 0.10mm, Pu = 75%).

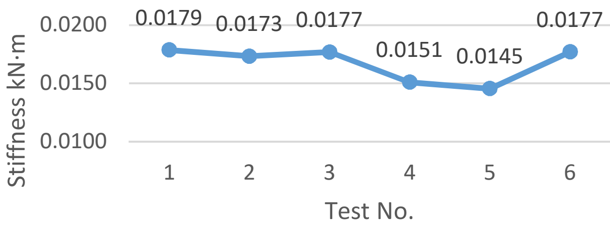


Fig. 24. Gear stiffness *R*1 (Hs = 0.15mm, Pu = 100%) with *R*2 (Hs = 0.15mm, Pu = 75%).

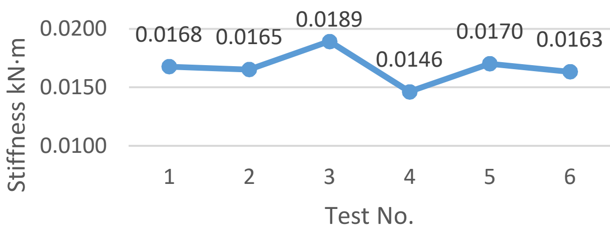


Fig. 25. Gear stiffness R1 (Hs = 0.15mm, Pu = 100%) with R2 (Hs = 0.15mm, Pu = 50%).

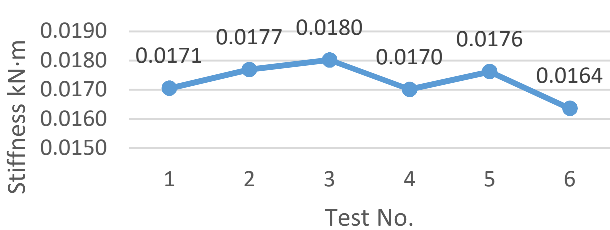


Fig. 26. Gear stiffness R1 (Hs = 0.15mm, Pu = 75%) with R2 (Hs = 0.15mm, Pu = 100%).

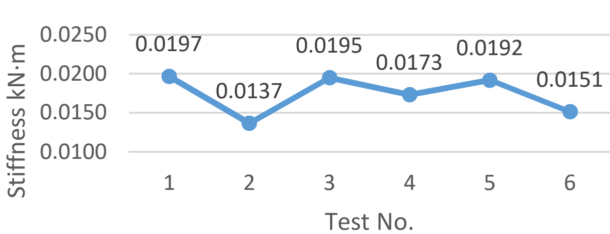


Fig. 27. Gear stiffness R1 (Hs = 0.15mm, Pu = 75%) with R2 (Hs = 0.15mm, Pu = 50%).

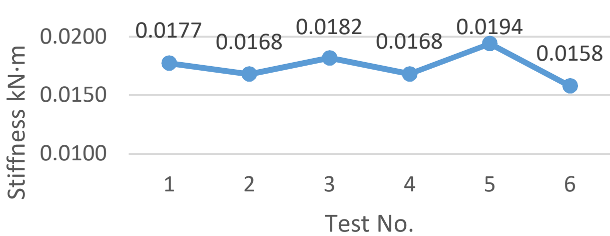


Fig. 28. Gear stiffness R1 (Hs = 0.15mm, Pu = 50%) with R2 (Hs = 0.15mm, Pu = 100%).

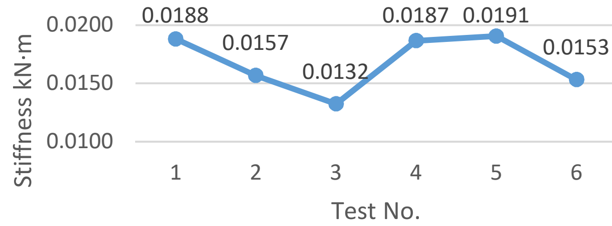


Fig. 29. Gear stiffness R1 (Hs = 0.15mm, Pu = 50%) with R2 (Hs = 0.15mm, Pu = 75%).

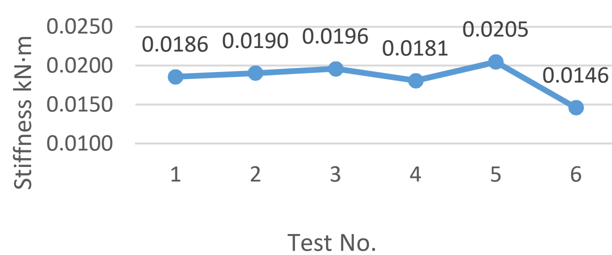


Fig. 30. Gear stiffness R1 (Hs = 0.20mm, Pu = 100%) with R2 (Hs = 0.15mm, Pu = 75%).

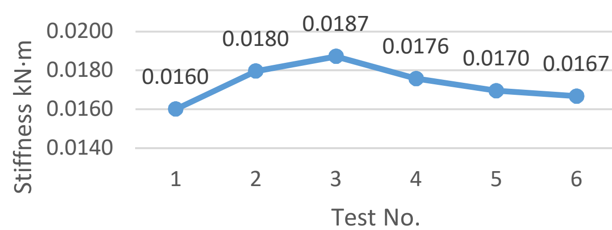


Fig. 31. Gear stiffness R1 (Hs = 0.20mm, Pu = 100%) withR2 (Hs = 0.15mm, Pu = 50%).

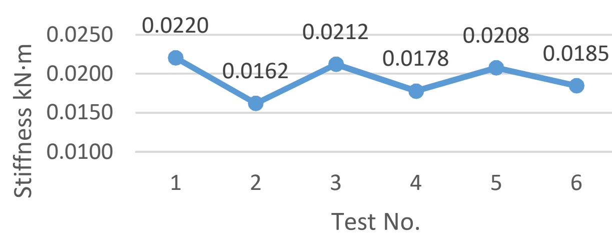


Fig. 32. Gear stiffness R1 (Hs = 0.20mm, Pu = 75%) with R2 (Hs = 0.15mm, Pu = 100%).

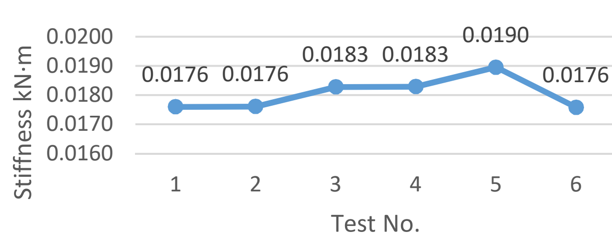


Fig. 33. Gear stiffness R1 (Hs = 0.20mm, Pu = 75%) with R2 (Hs = 0.15mm, Pu = 50%).

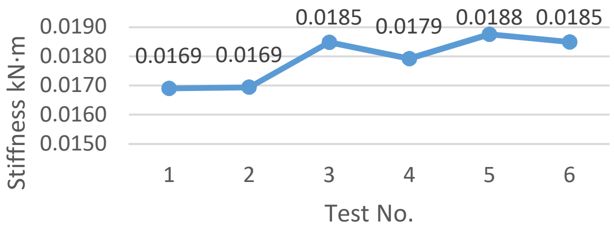


Fig. 34. Gear stiffness R1 (Hs = 0.20mm, Pu = 50%) with R2 (Hs = 0.15mm, Pu = 100%).

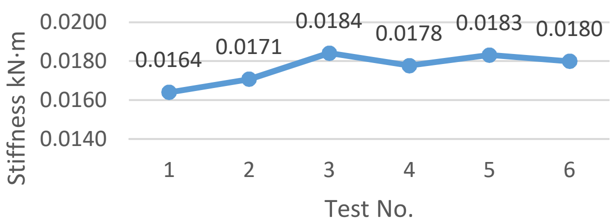


Fig. 35. Gear stiffness R1 (Hs = 0.20mm, Pu = 50%) with R2 (Hs = 0.15mm, Pu = 75%).

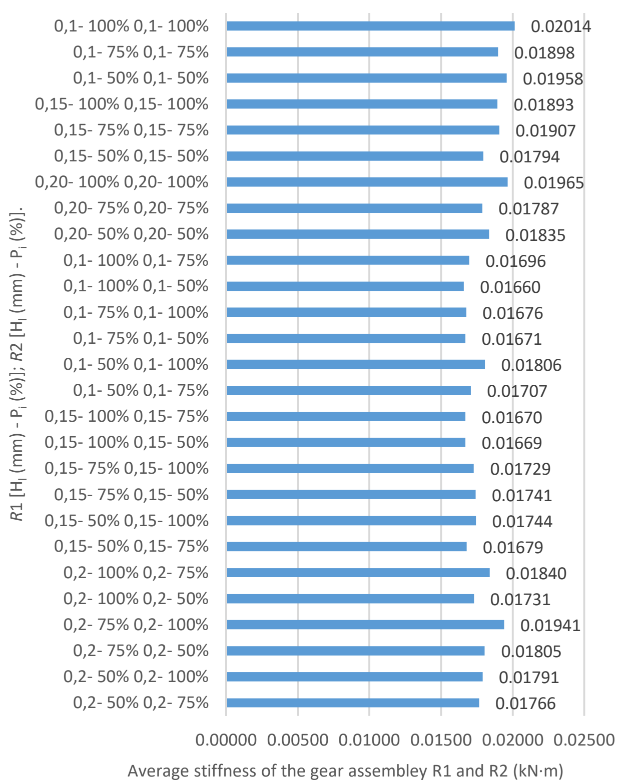


Fig. 36. Average stiffness of the R1 and R2 gear assembly.

The rigidity of the assembly of cylindrical gears was theoretically determined using FEA in Solidworks and experimentally validated using the device shown in Figure 8. The theoretical study of the gears stiffness revealed results that are presented in Figures 6 and 7, validated by the experimental results presented in Figures 9-36. It was found out that the percentage difference was 9.49%. Analyzing the results of the 162 experimental tests, an average value of the stiffness of the cylindrical gears with straight teeth 0.01791kN·m was obtained. For cylindrical gears, the minimum value of gear stiffness is 0.01323kN·m and was obtained for the gear with R1 (H_s = 0.15mm, P_u = 50%) and R2 (H_s = 0.15mm, P_u = 75%) and the maximum value of the gear stiffness is 0.02402kN·m and was obtained for the gear with R1 (H_s = 0.10mm, P_u = 100%) and R2 (H_s = 0.10mm, P_u = 100%). The height of the deposited layer (H_s) and the percentage of filling (P_u) influence the stiffness of the cylindrical gears assembly with straight teeth. Increasing the height of the deposited layer from H_s = 0.10mm to H_s = 0.15mm increases the stiffness of the gear by 2.34% and increasing from H_s = 0.10mm to H_s = 0.20mm increases stiffness by 4.02%. The increase of the filling percentage from P_u = 50% to P_u = 75% increases gear stiffness by 0.08% and the increase from P_u = 50% to P_u = 100% by 4.84%. The rigidity of the gears assembly with straight teeth is influenced by the percentage of filling (P_u) by 5.44% more than it is influenced by the height of the deposited layer (H_s). The novelty of this work consists in obtaining results of the maximum torque that can be applied to various printed gears characterized by different layer thicknesses and infill percentages until it deforms irreversibly in order to protect the energy source used in practical applications. There is a limited number of studies conducted on the subject. In [10], 6 types of PLA, from different producers, 2 types of ABS and 3 types of nylon all printed with the same parameters were compared and an optimal type of PLA that crushed at 0.018kN·m torque was.

IV. Conclusions

The objective of the current study was to determine an optimal combination of gear characterization by the printing and tested parameters. Furthermore, the result is similar to other studies using different PLA producers [10], so the study is considered valid. The paper reveals the maximum torque supported by 3D printed PLA (with certain parameters) and helps in choosing efficient variants of construction depending of the requirements of the application. The study is recommended to be applied to other types of 3D printed gears from various materials, using different additive manufacturing technologies.

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