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Original Research Article

A non-assembly approach for an additively manufactured finger prothesis

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Abstract: A new approach to print non-assembly mechanisms with reduced joint clearance is used to create an additive-manufactured finger prosthesis. Like other additive manufacturing methods, Fused Layer Modeling (FLM) requires a sufficient clearance between parts to archive moveable non-assembly mechanisms. A two-material design and a heat treatment allowed improving the accuracy of the movement beyond the printing limitations. It was shown that a functional finger prosthesis can be produced using this technique.

I. Introduction

Prosthetic devices have to be highly customized to be useful and comfortable for the user. Therefore, additive manufacturing is an attractive manufacturing method for these devices.

For hand protheses some well-known designs for additive manufacturing have been published. The Raptor Hand [1] is an assembly design usually built from one material. The Kinetic Hand [2] also uses an assembly approach but with different materials, whereas the Delft Hand [3] is a non-assembly design consisting of a single material.

I.I. Limitations of the current designs

Movable hand protheses are complex mechanisms. For the assembly designs, many separate parts have to be printed and assembled. The process requires a lot of time. Due to the limited accuracy of the printing process, sufficient clearance is necessary for the assembly. This leads to significant play in the joints. The Kinetic Hand [2] uses thermoplastic elastomer elements for the finger joints to reduce the noise during motion and increase the quality of the movement.

Choosing a non-assembly design like the Delft Hand [3] can avoid the assembly effort. For such a non-assembly design, a clearance between moving parts is mandatory for production to ensure that the parts stay separated during the printing process. The resulting play in the joints tends to be even larger compared to the assembly design. To overcome this crucial limitation special properties of the printing process and the involved materials have been used in this work.

I.II. Non-assembly mechanisms

Lussenburg, et al. describe a possible classification for non-assembly mechanisms [4]. According to these authors, the Delft Hand is a mono-material / multi-body mechanism. Furthermore, the work has shown that there has been only little published research in the field of multi-material / multi-body approaches for non-assembly mechanisms. A first investigation of Harden et al. [5] has started developing a multi-material / multi-body approach filling this gap. This approach is used for the proposed design. Fig. 1 shows the general idea. The inner and outer part of the joint are printed using different materials. Making use of different shrinking behaviors, during a heat treatment the outer body contracts onto the inner body reducing the joint clearance [5]. The reason for the shrinking lies in the production process. During FLM printing, high shear stresses are introduced into the molten material. The shear stresses cause strong orientation of the macromolecules within the printing plane (x-y-plane). Since the materials cool down below the glass transition temperature quickly, most of the orientation remains frozen in the part. Heating the material slightly above the glass transition temperature will start a relaxation process. This will cause the part to shrink in the x-y-plane and expand in the z-direction.

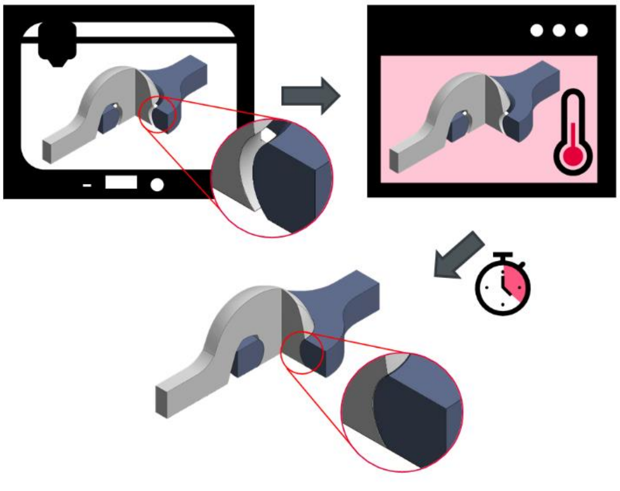

Figure 1: Process to create low clearance non-assembly mechanisms according to Harden et al. [5]

II. Material investigation

Previous investigations [6] have shown that polylactic acid (PLA) is a promising material for the outer body of the described process due to its pronounced shrinking behavior in a heat treatment subsequent to FLM printing. A thermo mechanical analyzer TMA 402 from Netzsch Gerätebau GmbH was used to measure the dilatation behavior. Small test cubes of 7 mm edge length were printed for the analysis of the dilatation behavior in different directions. The results of a PLA are shown in Fig 2. A heating phase from room temperature to 70 °C with a heating rate of 2 K/min was followed by an isothermal phase for four hours, before the cooling with 0,2 K/min started.

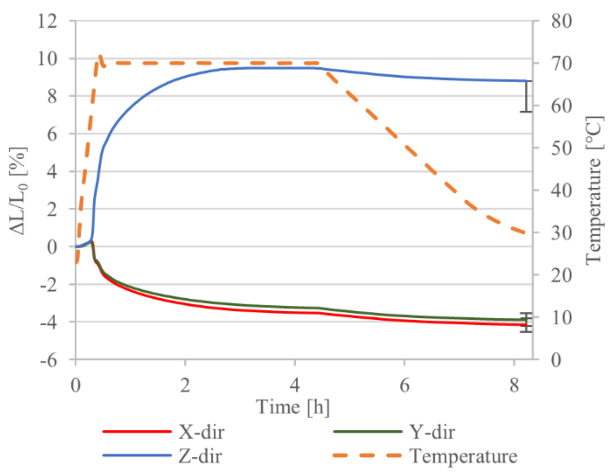

Figure 2: TMA results for PLA (4 h at 70 °C), [7]

Using different materials for the inner and outer part of the joint offers the possibility of using the contracting effect of the orientation relaxation to reduce the clearance after the printing process. This requires the glass transition temperature of the material for the outer part (here PLA) to be lower (about 10 degrees or more) than that of the inner part. The different glass transition temperatures ensure that the inner part shows little geometric change while the outer part shrinks in size. Igus i150, a glycol modified poly ethylene terephthalate with embedded polytetra-fluorethylene particles - PET-G/PTFE fulfills this requirement. In addition, the presence of PTFE particles can reduce the coefficient of friction and wear rate. The TMA results for i150 are shown in Fig. 3. The same trend as for PLA is recognizable but the magnitude of effects is significantly smaller.

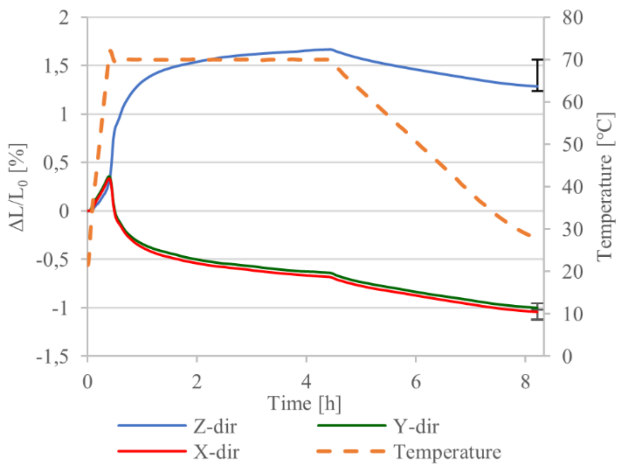

Figure 3: TMA results for i150 (4 h at 70 °C), [7]

First tests for revolute joints indicated that the low stiffness of PLA at 70 °C can cause deformations of the mechanism during the heat treatment. To avoid this unwanted geometry change, only the parts forming the outer joint geometry are printed from PLA. Process parameters like layer thickness, printing speed, etc. influence the orientation and relaxation process of the polymers. Therefore, the design clearance is selected for a specific set of printing parameters.

The clearance before and after the heat treatment was measured in a tensile test setup adding a spring between the sample and the actuator allowing larger deformations without overloading the specimen. For evaluation, a force-displacement curve is plotted. Fig. 4 exemplarily shows the results of a measurement of a sample with 500 µm circumferential design clearance before and after heat treatment in comparison. For idealized circular geometries, the region of displacement where no force occurs is twice the circumferential clearance. Small misalignments and the staircase effect at the surface cause a hysteresis in this region. Therefore, the displacement between the deviation of the linear elastic deformations has been used for evaluating the clearance. The results of the untreated specimen show that the actual clearance (ca. 550 µm) after printing is about half the designed clearance (500 µm circumferential). This proves the limited accuracy while printing. Comparing the untreated sample to the sample after heat treatment, it can be seen that there is no step-like hysteresis. This indicated the absence of clearance (at least in the detectable magnitude) after the heat treatment, while the joint remains movable.

Fig. 5 shows a micro-CT scans of two different joints before the heat treatment. The staircase effect on the inner surfaces of the joint is clearly visual.

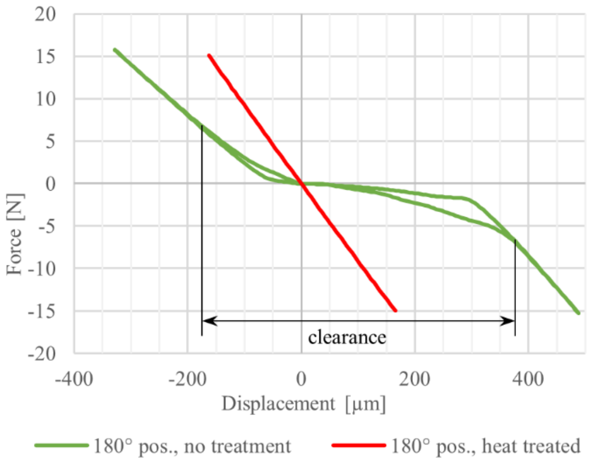

Figure 4: Force displacement curves to determine the clearance of the joints, 500 µm circumferential design clearance [7]

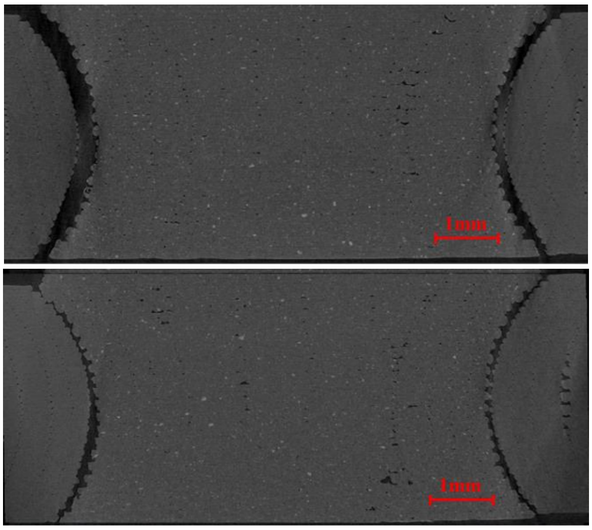

Figure 5: Micro-CT scans of two joints before the heat treatment, top: 500 µm circumferential design clearance; bottom: 300 µm circumferential design clearance [7]

III. Biomedical Application

This study orientates on the last three joints – DIP, PIP and MCP – of the index finger (refer to Fig. 6). The concept of the low clearance multi-body / multi-material non-assembly mechanism was used to build a prototype of a finger prothesis. The DIP and PIP joints are designed as revolute joints (refer to Fig. 7). To restrict the motion of these joints to a range similar to the natural finger, limiters are included in the design. Even though the actuation system is not yet integrated into the current prototype, the finger is prepared for mechanical actuation using tendons for the flexion and elastic bands to extend the finger. Therefore, design provisions are integrated to guide bands accordingly. The actuating unit will be placed in the area of the wrist. The MCP joint was designed as ball joint with additional features to limit/suppress the torsional rotation (refer to Fig. 8), since the natural finger allows only passive torsional rotation. The final design of the non-assembly finger prosthesis is shown in Fig. 9. The red portions represent PLA, the white parts i150.

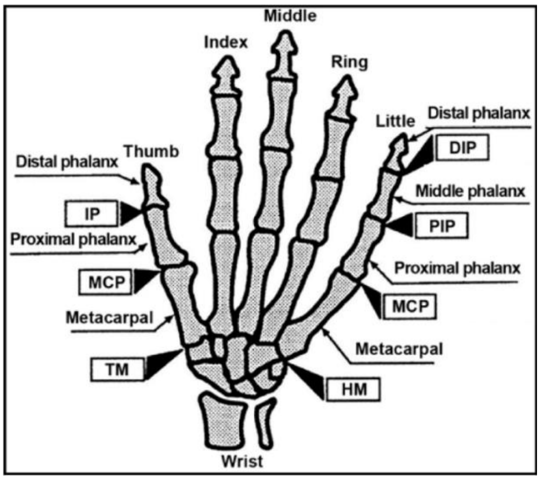

Figure 6: Anatomy of a human hand [8]

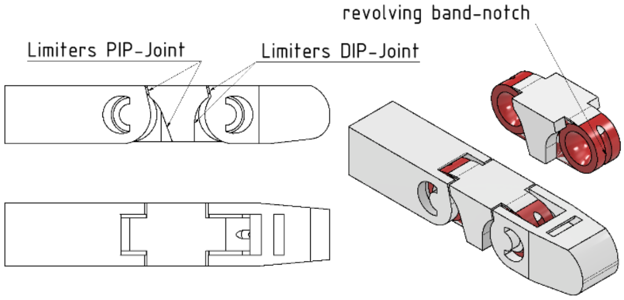

Figure 7: Design of DIP and PIP joints [7]

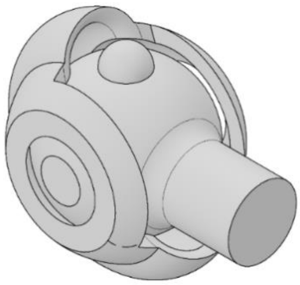

Figure 8: Design of MCP joint [7]

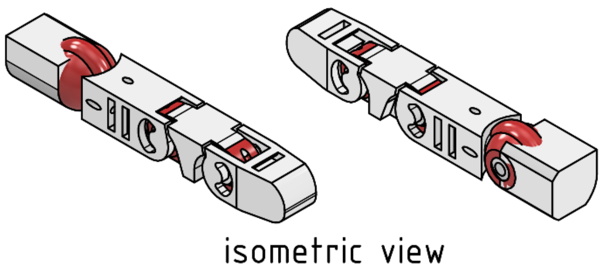

Figure 9: Final design for the complete finger [7]

A commercial Ultimaker S3 printer with a dual extruder has been used to print the finger protheses. Even with the dilatation values measured via TMA for cubic samples [5], some iterative adjustments in the design were necessary. One of the reasons might be the asymmetry of the single members of the prosthesis. Furthermore, the adjacent material influences the shrinkage during the heat treatment causing a deviation from the TMA results. Photos of the final version are shown in Fig. 10.

Figure 10: Printed finger prothesis [7]

IV. Results and discussion

To turn the multi-body / multi-material non-assembly mechanism into a fully useable prosthetic device further development is necessary. The printed finger is a proof of concept. Due to the orientation of macromolecules induced by FLM printing, the material's dilatation during the subsequent heat treatment reduces the joint clearance, provided that the involved materials are matched properly. However, printing a complete hand using this approach will require a concept for the support structure, since the rotation axis of the revolute joints so far need to be perpendicular to the printing plane. Further investigation of design principles for different joints might be beneficial to overcome this limitation. The opportunities of a multi-material printing approach with more than two materials should be investigated as well. At least soluble support material (for support structures) as third material would greatly reduce the post processing effort required. In addition, a deeper investigation into the material behavior is required to minimize the number of iterations needed to finalize the joint clearance.

Nevertheless, the design solution presented in this work is only a non-assembly mechanism regarding its structural components. All components for actuating the mechanism need to be assembled afterwards. However, compared to the Raptor Hand [1] or the Kinetic Hand [2] this approach greatly reduces the assembly effort since the complete structural assembly is omitted. In comparison to the Delft Hand [3], the assembly effort is increased since the Delft Hand has a non-assembly approach for the actuating mechanism as well. On the other hand, our design solution offers reduced joint clearance and a larger degree of freedom making movements possible closer to the natural finger compared to the other three examples.

The feasibility of the described process was shown with the materials PLA and PET-G/PTFE. However, especially PLA might not be the material of choice regarding mechanical strength and tribological performance. Therefore, other material combinations for this process should be investigated.

V. Conclusions

The presented design proofs that additively manufactured multi-material / multi-body non-assembly mechanisms are suitable to build finger protheses with low clearance in the joints after heat treatment. Besides the increased degrees of freedom, it can be expected that the reduced clearance will allow more precise movements of the proposed design comparing to currently available assembly as well as non-assembly approaches produced via additive manufacturing.

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Author's statement

Conflict of interest: Authors state no conflict of interest.

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