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# A SURVEY OF ADDITIVE MANUFACTURING PROCESSES APPLIED ON THE FABRICATION OF GEARS

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**ABSTRACT**: *T*he geometric complexity of mechanical components of mechatronic systems is a challenge to apply Additive Manufacturing. The focus of this study is to evaluate the potential of AM processes for the fabrication of different types of multistage spur gears, bevel gears, worm gears, Harmonic drive gears, cycloidal drives and pumps. The precision of different AM technologies is compared. Material behavior is investigated on a gear test rig. The opportunities and limitations of processes using plastics for the fabrication of gears are discussed in this paper.

## INTRODUCTION

Geometric complexity of a part, small-scale or tailored fabrication, just-in-time or short time-to-market requirements are the criteria for the application of additive manufacturing instead of conventional manufacturing, as milling, injection casting or high pressure casting, plastic forming or metal forming. Additive manufacturing can help to integrate mechatronic components to more compact units and so facilitate miniaturization. Typical mechatronic components of high geometric complexity and diversity are gears. The manufacturing of a gear with helical, spiral, hypoid or cycloid geometry is resource-intensively realized by conventional manufacturing processes. This paper gives a survey on additively fabricated gears by different technologies. Surface qualities and material properties are compared, optimization loops are performed to reduce the lack of precision adherent to AM processes. A target of the investigations, described here, is to provide rapidly prototypes of plastic gears in a first step, followed by additive fabrication of metal gears.

The rapid product development of a gear, shown in figure 1, starts with the creation of a 3D-CAD model, usually followed by FEM simulation. The next step of the process chain requires at least one optimization loop, due to the insufficient accuracy and precision of additive manufacturing. The optimized gear is finally built. The efficiency of the gear, friction and wear of bearings and teeth can be analyzed, tensions and deformations simulated by FEM can be verified on a test rig.

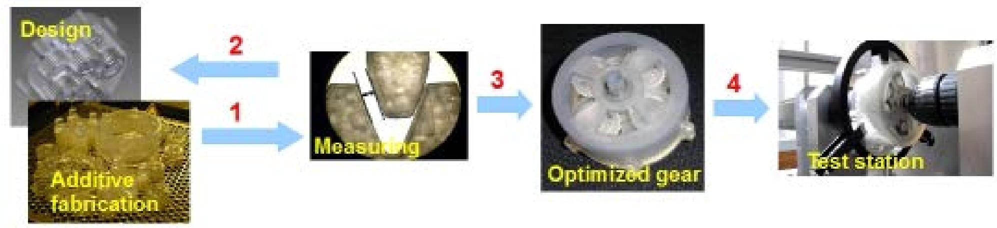


Figure 1. Process chain Additive Manufacturing of high reduction gears.

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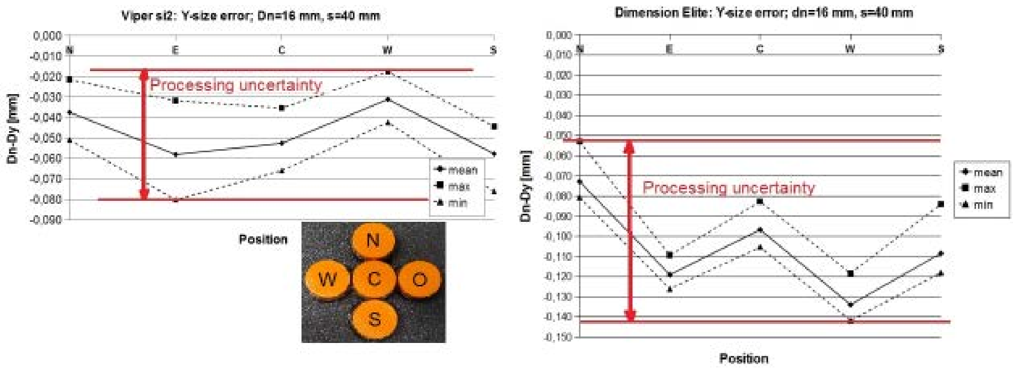


Figure 2. Deviation of Y-diameter from nominal size 16 mm at 5 platform positions.

## PROCESSING UNCERTAINTY

### Analysis of processing errors

Rapid Manufacturing requires the capability of a process to reproduce a defined quality of a part. In order to meet the decision for the selection of a machine and its technology the characteristics of its processing uncertainty must be known in advance. The processing uncertainty of an AM machine must be investigated for different nominal sizes of a part due to its non-linear behavior to provide a database containing reference values for backlash of bearings and teeth of the gear.

To determine the processing uncertainty for a nominal shaft size of 16 mm five batches of parts as shown in Figure 2 were fabricated. Two diameters of each part were measured several times in X and in Y direction and the resulting roundness error was estimated. The same procedure was performed by use of a FLM professional 3D printer and of a personal 3D printer.
Figure 2 displays the deviations at the example of the nominal Y size. It also shows a mean deviation from the nominal size of diameter of about 60 µm at position C on the platform of a SLA machine, about 25 µm at a professional printer. The results allow to compare accuracy and precision of a production machine, a professional 3D printer and a personal 3D printer dependent of a position on the building platform of the machine. If the nominal size is varied, the processing uncertainty behaves non-linearly. For example, it increases by factor 1.7 given a nominal size rate of 2.7 at a Viper si2 SL machine.

### Quality control strategies

The accuracy of a machine is due to systematic errors, which could be compensated by the off-line optimization of the manufacturing process as displayed in figure 1. After the measuring in step 2, step 1 is iterated.
The processing uncertainty of a machine is caused by accidental errors. A strategy to reduce them is in-line process control, see Kruth et. al. (2009), Yadroitsev et. al. (2012).
Another approach performed by off-line quality control is discussed in Berger (2010). The methodology is to tolerate a decrease of accuracy for a gear, relating to a nominal size as for instance that of the pitch circle, but to increase precision, i. e. reduction of s. That needs a quality control procedure after step 3 shown in figure 1.
Figure 3 displays the components of eight micro Harmonic Drive gears placed concentrically on the building platform. Each gear consists of six components. To reduce the variation of the s between identical gear component pairs, i. e. their accidental error, each gear

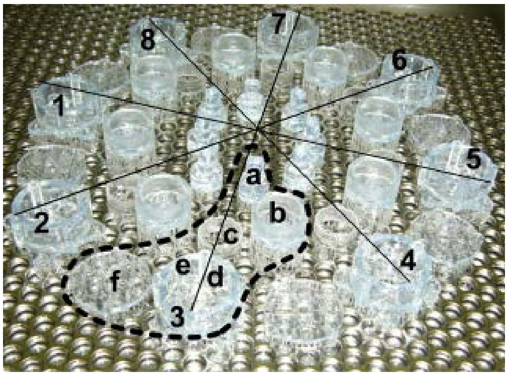


Figure 3. SL Building platform with the components of eight micro Harmonic Drive gears.

component is sorted, graded according to the deviation of its nominal size, and then combined with the appropriate pair component of the same grade. By this strategy the range of s of pairs of identical gear components can be reduced from 56.6 µm at a standard deviation of 23.8 µm to 20 µm at a standard deviation of 7.9 µm. The measurements were conducted manually, but the procedure could also be automated by use of an image processing system.

Table 1. Properties of AM plastics

| | Tensile strength [MPa] | Tensile modulus [MPa] | Elongation at break % | Heat-deflection temperature [°C)] |
|---|---|---|---|---|
| ABS | 46 | 2,000 | 40 | 110 |
| ABS-M30 | 36 | 2 | 4 | 110 |
| ULTEM 9085 | 72 | 2200 | 6 | 153 |
| Accura 60 | 60 | 3,000 | 14-22 | 50 |
| Somos Nano Tool (nanocomposite) | 62-78 | 11,000 | 0.7-1 | 225 (UV+heat postcured: 260) |
| FullCure 720 | 60 | 2,870 | 20 | 49 ($T_g$) |
| Pa 2200 | 45 | 1,700 | 20 | 140 |

## CHARACTERISTICS OF AM MATERIALS

### Physical properties of AM materials

Different as at metal, material properties of plastics are weak points of AM technologies.

Duroplastic photopolymers used for additive manufacturing tend to material degradation due to aging, evoking loss of elasticity and increase of brittleness. Consequently, applications connected with mechanical deformation and high temperature in wet environment should be realized rather by thermoplastic-based technologies as fused layer modeling (FLM) or selective laser sintering (SLS) than by photopolymer-based technologies, Berger (2011). Table 1 shows material properties

Figure 4: Components of a micro Harmonic Drive gear with tooth module 0.2 mm.

of epoxy resins and acrylates available for additive fabrication. Epoxy resins are used for stereolithography (SL), acrylate photo-polymer resins are applied for DLP, MJM and PJM.
For reference, the thermoplastic serial material ABS (acrylonitrile butadiene styrene) is added to the table. Compared to the duroplastic epoxy resins and acrylates the thermoplastics ABS and PA show less influence of aging.
Nano-filled resins postcured by heat and UV-light are high performance plastics. The flexibility of a duroplastic material can be increased by blending with acrylates.

**Structure of AM materials**
Additive manufacturing can roughly be divided up relating to the state of aggregation of the building material, which can be gaseous, liquid or solid. Furthermore it can be divided up depending on the type of binding mechanism. It can be melted, fused or glued together. Due to its binding mechanism, stereolithography and selective laser sintering, if the powder particles are completely fused, i. e. melted, offer advantages relating to material isotropy, compared with fused layer modeling (FLM) or 3D printing (3DP), where the binding is performed by an adhesive.
Figure 4 shows the components of a micro Harmonic Drive gear with tooth module 0.2 mm. They were fabricated by different additive manufacturing technologies to compare the feasibility of small details. Due to its liquid building material, SL is in advantage. The FLM part in figure 6 was fabricated using ULTEM, its tooth geometry is partially lost. A flexspline produced by SLS PA 2200 is shown in figure 6 at the left, its circular spline at the right. Their tooth geometry is completely lost.
Figure 5 displays parts of a gear fabricated by PJM technology at the left. The parts of gear at the right were produced on an Invision si2 machine by MJM technology.


Figure 5: Left gear: module 0.75 fabricated by PJM, right gear: module 1.5 fabricated by MJM.

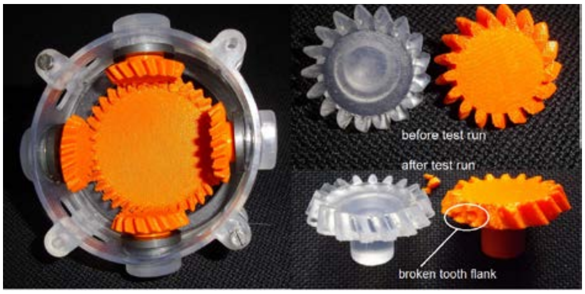


Figure 6: Planetary gear components fabricated by LS and FLM.

**Strength of AM materials**
A planetary gear was fabricated on a Viper si2 SL machine and on a Dimension Elite FLM machine. Standard bushings were used to reduce wear. Each gear run for a time span of 60 minutes under a load torque of 0.25 Nm on a test rig. A Kissoft calculation resulted to Hertzian pressure of 3.84 MPa and tooth root stress of 10 MPa. The SL bevel gear does not show any wear nor break. Only one of four FLM bevels was damaged by break at edges of tooth flanks, but there is no visible wear (figure 6). Both gearboxes affected loudness, apparently due to tooth backlash.

## APPLICATIONS

**Planetary gears, differential gears**
Figure 7 displays types of planetary and differential gears fabricated by stereolithography. Versions with spur gear wheels, helical gear wheels, spiral bevel gear wheels, hypoid gear wheels were realized, and each of them optimized by FEM. Test results were: The transferable torque was lower then 20% as expected by simulation.

**Worm gears**
Worm gears can realize high reduction of motions. As at cycloidal gears their geometry is complicated and challenging for additive fabrication. Figure 7 displays functional worm gears produced by stereolithography.

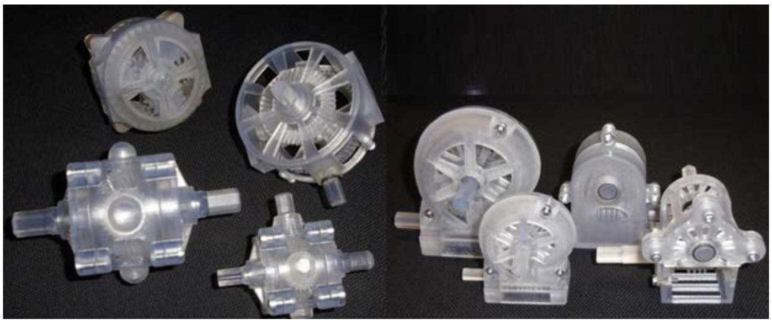

Figure 7: Differential gears and worm gears, SL

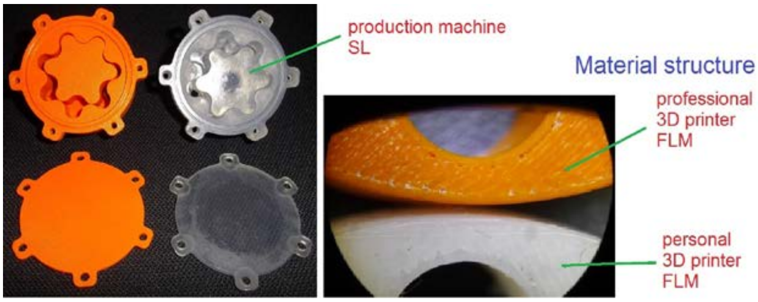


Figure 8. Cycloid pumps

**Cycloidal gears and pumps**

The additive fabrication of single-stage and multi-stage cycloidal gears is described in Berger (2009). Cycloidal pumps with different numbers of teeth at the ring gear were fabricated on a Viper si2 machine, on a Dimension Elite machine and on a UP! personal 3D printer. The use of a personal 3D printer required an additional compensation step according to figure 1, due to lower accuracy of this machine. The surface textures at identical pump parts fabricated on a professional 3D printer and on a personal 3D printer can be compared in figure 8.

## CONCLUSIONS

Low levels of positioning and repeat accuracy, backlash of the gearboxes and limitations of building materials in plastics are disadvantages adherent to the state-of-the-art of existing additive manufacturing technologies. The additive manufacturing of gears can be applied, when the required accuracy does not fall below ISO tolerance grade 10 and the allowable temperature and strength are of secondary order. If custom tailored solutions must be provided in short periods of time, conventional subtractive manufacturing drops out. If fatigue resistance and higher performance are required, the additive fabrication by metal technologies can be focused.

## REFERENCES

Kruth, P.,Mercelis, P., Van Vaerenbergh, J., Craeghs, T. (2007), *Feedback Control of Selective Laser Melting*, Proc. pp. 521-527; VRAP 2007, Leiria, 17th–22nd September 2007: Rotterdam, Balkema.

Yadroitsev, I., Gimadeeva, D., Bertrand, Ph., Smurov (2012), *Selective LaserMelting of Ti6Al4V alloy*, 13th Annual RAPDASA Conference, Kwa Maritane, South Africa.

Berger, U. (2010). *A Strategy to Increase the Precision of the Direct Manufacturing of Micro Gears Due to Error Analysis of a Stereolithography Machine*, 4th international conference polymers & moulds innovations, Ghent, Belgium, 15th -17th September 2010, proc. pp. 88-92.

Berger, U., Mäule, B. (2009). *Rapid Manufacturing of High Reduction Polymer Gears by Use of Stereolithography*, Proc. pp. 613-617; IEEE/ASME Conference on Advanced Intelligent Mechatronics, Singapore, 14th -17th July 2009: IEEE Catalog Number: FP09775-CDR.

Berger, U. (2011). *Rapid Manufacturing of Components for the Automation– Chances and Limitations of Stereolithography*, RAPDASA 2011, Vaal University of Technology, South Africa, 2nd– 4th November 2011, conference proceedings.