Cylindrical Gear Rapid Manufacturing Study (Part II)
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Abstract: One of the objectives of the main author’s research work, in the telemanufacturing field, is to design and develop an online software system for the production management of rapid manufacturing centres and remote customer order handling. The system is intended to include special aspects for the rapid manufacturing of cylindrical gears, to make it possible to benefit of already existing expertise in the gear calculus field. For this reason, research is being conducted to determine special requirements for gear rapid manufacturing and to compare the results of experiments, obtained with different rapid manufacturing technologies. From a reducer design, a cylindrical gear has been taken and scaled to obtain a non-standard gear module which justifies the need for fabrication through rapid prototyping / 3d printing. This paper presents the results of two gear rapid prototyping experiments as well as the drawn conclusions.

Key-Words: gears, rapid manufacturing, rapid prototyping, telemanufacturing

1 Introduction
The activity of the AMTS (Advanced Manufacturing Technologies and Systems) research department of the Transilvania University of Brasov includes several objectives regarding the teleengineering field, especially in regard to telemanufacturing. The telemanufacturing field has speeded up its development in the last decade, especially due to the world-wide propagation of broadband Internet. The concept of a digital factory has been rapidly gaining ground, integrating even telepresence applications [1]. Online CAD/CAPP applications are also emerging [2].

Dr., dipl. eng. Bogdan Deaky, as a postdoctoral researcher, is responsible for the implementation of the teleengineering objectives. While most of the objectives are aimed at remote monitoring (and partial control), one of them aims at developing an online application for customer order and production management, dedicated to rapid prototyping / rapid manufacturing centres.

Different approaches for web-based rapid prototyping and manufacturing systems do exist, in a more or less advanced stage. An up-to-date review can be found in [3]. The system presented in [4] has a useful feature, namely a stereolithography-oriented online pricing engine (OPE) based on build-time prediction algorithms.

For the online application that will be developed for customer order handling and production management, the main author proposed supplementary features, to make it accommodate specific needs of cylindrical gear rapid manufacturing. This decision was taken in order to add an innovative feature to the application and in order to leverage existing expertise in the cylindrical gear calculus field (a PhD thesis in the field). To achieve this, it is obviously important to at least understand the required input data, the manufacturing process and the capabilities of the different rapid manufacturing processes. Therefore, it was decided to manufacture the same gear part by means of several rapid manufacturing technologies, especially rapid prototyping.

During this study, knowledge is being gathered by observing the manufacturing process and its prerequisites. A later comparison between more manufactured gears will also show the strengths and weaknesses of each process (from the gears field perspective). The comparison is not intended to be a competitional classification of different methods and machines. Its purpose is to find suitable rapid manufacturing methods, while considering the possible application fields and the different possible exploitation scenarios of the obtained parts.

In order to have access to different rapid prototyping machines, collaborations with other departments and research centres have been initiated, allowing adding part of their infrastructure to the existing AMTS research department infrastructure. For this paper, the HPMPMS (High Precision Mechanical Products and Mechatronic
systems) research department helped out with the Stratasys Dimension Elite machine.

The first two parts that were manufactured, using the PolyJet and FDM (Fused Deposition Modelling) methods, have been presented in an earlier paper with a similar title as this one (part I).

This second paper includes information about other two parts produced, using the Z-Printing method and, again, the FDM method. The new part manufactured with the FDM method was produced on a newer machine and some observations regarding the evolution of FDM machines will be noted.

2 The Gear Design

The earlier paper (Part I) discusses this topic more broadly and includes a picture of the reducer from which the gear was taken, a few introductory details about the Direct Gear Design method as well as some other considerations.

Rapid prototyping methods are certainly very suitable to quickly manufacture non-standard gears, for example, like those that are obtained by means of the Direct Gear Design method [5]. To justify the rapid prototyping of a gear, the CAD drawing of a gear with standard parameters, taken from a reducer, was scaled by a factor of 0.7. This allowed for a non-standard gear module (2.1mm instead of 3mm).

The final 3D model of the gear to be prototyped can be seen in fig. 1. The gear parameters are shown in table 1.

Fig. 1. Gear to be manufactured

<table>
<thead>
<tr>
<th>Table 1. Gear parameters</th>
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<tbody>
<tr>
<td>Parameter</td>
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<tr>
<td>Module</td>
</tr>
<tr>
<td>Number of teeth</td>
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<tr>
<td>Helix direction</td>
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<td>Helix angle</td>
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<tr>
<td>Pressure angle</td>
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<tr>
<td>Width</td>
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<td>Shaft diameter</td>
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3 The Gear Manufacturing Process

As mentioned, two gears have been manufactured previously, using the PolyJet and FDM (Fused Deposition Modelling) methods. To achieve this, an Objet EDEN 350 machine and an older Stratasys FDM machine have been used.

Please refer to the previous paper (Part I) for snapshots and details of the manufacturing processes.

This paper presents the manufacturing processes (and some conclusions) of two new gears. For this, the chosen gear was manufactured by means of two different rapid prototyping methods: (Z) 3D printing, using the existing Z Corporation’s ZPrinter 310 Plus machine at the local department, and FDM (Fused Deposition Modelling), on a Stratasys Dimension Elite machine, with the kind assistance of the AMS research department. The processes and resulted parts are presented bellow.

3.1 Manufacturing using the (Z) 3D printing method

The machine used by the authors was a ZPrinter 310 Plus (see fig. 2) manufactured by Z Corporation. The software used to manage the process was ZPrint.

The ZPrinter 310 Plus is an entry level 3D printing machine that offers high production speed (although with less precision and fragility). Please note that Z Corporation also offers the Z Builder series machines which they refer to as prototyping systems, and produce high-precision parts using a photopolymer material. The fabrication method used by the ZPrinter is based on the Inkjet technology (it actually even uses a HP10 cartridge) but it jets binder instead of ink over the composite material powder.

The gear was manufactured amazingly fast, in only 40 minutes, to which 60 minutes of consolidation time has to be added (the part remains in the machine, at 37°C temperature). No snapshot of the manufacturing process is attached, because the part itself is buried in powder during the whole
process. Fig. 3 shows a snapshot taken after the consolidation treatment was complete and the gear was partially dug out. Fig. 4 shows the gear after it has been removed from the machine.

Afterwards, the gear was cleaned (with a brush and compressed air) and a layer of infiltrating agent (Z-Bond 101 – Medium Strength Cyanoacrylate Infiltration System) was applied, which superficially hardened the gear. Fig. 5 shows the final gear.

Different types of material may be used (composite, elastomeric) and the more expensive ZPrinter models can even manufacture colour solids (24-bit colours) The material used for our part was ZP131, while nowadays the latest available composite material is ZP150 (with higher toughness).

3.2 Manufacturing using the FDM method

The machine used this time by the authors was a Stratasys Dimension Elite (see fig. 6), a newer model when compared to the previously used Stratasys FDM machine. The software used to manage the process was CatalystEX.

When using FDM (Fused Deposition Modelling), a plastic wire is unwound from a coil and supplies material to heated extrusion nozzles which can turn the flow on and off (separate nozzles for part and support materials). The part is manufactured by extruding and laying down thermoplastic material (0.1778 mm wide in this case) to form layers. Fig. 7 shows a snapshot taken during the manufacturing process.

The new support materials (SST - Soluble Support Technology) can be melted away. Fig. 8 (next page) shows the bottom of the manufactured part, before removal of the support material.
There are special cures to melt away the support material. Fig. 9 shows the finished part (meshing with a pinion), after removal of the support material, this time by means of a chemical cleaning bath. The material used was Acrylonitrile Butadiene Styrene (ABS) plus.

### 4 Conclusions

A detailed study of the manufactured parts will be published in the future. This paper only shows two additional manufactured parts. With these, the general conclusions that were drawn in Part I are reconfirmed. To those we can add:

- There can be very big differences between materials used by different rapid prototyping methods and the resulting gear capabilities.
- There can be very big differences regarding the total manufacturing time (we experienced from 2 hours to 17 hours).
- The gear produced on the ZPrinter seems to have the lowest precision and is the most fragile, but it was produced much faster and cheaper.
- The newer Stratasys machine had produced the gear twice as fast, with better precision; the new SST support material is much easier to remove.
- The Stratasys sparse model interior generation algorithms have improved over the years.

A comparison methodology is being developed to take into account these and other aspects.

The purpose of this research is to get good information regarding gear manufacturing capabilities of each studied method, a good decisional methodology regarding when to use which method and information for time and pricing quotes.

Most of this information will be integrated into the online application for client order and production management which will be developed in the future.

This study might however prove useful at least to those gear specialists that are new to the rapid prototyping field.

Readers who would like to collaborate to help make this study bigger are welcome to contact the main author.

### 5 Acknowledgement

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**References:**


