REQUIREMENT: NC IN ADDITIVE MANUFACTURING

Deliverable D6.1

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EXECUTIVE SUMMARY

This deliverable 6.1 “Requirement: NC in Additive Manufacturing” of the CAxMan project corresponds to a technical report describing the requirements for subtractive technology complementary to the Additive Manufacturing (AM) process. The deliverable also refers to MS1 “Requirements”.

The deliverable D6.1 provides a description of the current process (state of the art) for the subtractive technology and the Numerical Control (NC) of the Machining process for the two use cases selected within this project.

In addition, the advantages of the proposed approach coupling AM and Subtractive Manufacturing are discussed as requirements and expectations of the use case providers with reference to the production process.

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1 INTRODUCTION

1.1 WORK PACKAGE CONTEXT

The present deliverable belongs to Work Package (WP) 6 "Numerical Control". The objectives of this WP are:

- To develop workflows for efficient machining of workpieces produced by layered or thread based AM.
- To exploit different combinations of the virtual models created in the project workflows (e.g., CAD-model, or the expected shape after AM) with the measured shape after AM, for NC path planning for workpieces produced by AM.
- To exploit and extend the iso-geometric approach developed in the TERRIFIC project for use on workpieces produced by AM.
- To devise strategies for finishing machining of only vital interfaces of workpieces produced by AM.
- To support the use cases with NC-technology.

In particular, this deliverable corresponds to the activities carried out in Task 6.1 "Interoperability to design. Virtual models and measured work pieces produced by Additive Manufacturing", led by MISSLER and developed in collaboration with STAM and NOVATRA.

The goal of this task is to define the requirements to develop the subtractive manufacturing process on the parts initially produced with AM. In particular a workflow will be developed from the designed part to just the finishing phase of the manufacturing process. As the starting point of the workflow can be different (e.g., it can start from the Quality control (WP5) or can be virtual (WP3)), it is necessary to obtain a complete representation of all data before starting the analysis of the residual or extra material that must be removed by a traditional subtractive technology.

2 NUGEAR USE CASE

The scope of this chapter is to describe the state of the art techniques evaluated and/or used to manufacture the NUGEAR, an innovative gearbox based on the mathematical concept of nutation coupled with bevel gears.

Section 2.1 reports a brief introduction to bevel gears, their features and the difficulties related to manufacturing such components. A short introduction to standard methods for producing bevel gears is given.

The objective of Section 2.2 is to analyse the state of art techniques used in the previous projects focused on NUGEAR, with particular reference to the Electrical Discharge Machining and gear milling.

2.1 INTRODUCTION TO BEVEL GEARS AND THEIR MANUFACTURING

2.1.1 Nomenclature and kinematics

Gears are crucial components for modern precision machinery as a means for the power transmission mechanism. Due to their complexity and unique characteristics, gears have been designed and manufactured by a special type of machine tools, such as gear hobbing and shaping machines. The machines and processes that have been developed for producing traditional gears are among the most ingenious existing. Whether produced in large or small quantities, in cell, or job shop batches, the sequence of processes for traditional gear manufacturing requires four sets of operations:

- Blanking
- Gear cutting
- Heat treatment
- Grinding

Depending on their type and application or required strength and resistance, gears are manufactured by casting, extruding, forging, powder metallurgy, plastic moulding, gear rolling and machining. Among these processes, machining is more frequently used for high precision gears.

Among the several kinds of existing gears, it is harder to manufacture bevel gears than cylindrical gears. These difficulties are due to the particular shape of the gear, which is conical instead of cylindrical; therefore, the gear cutting process is much more complicated than for the common spur gears.

Among bevel gears, there are two different cases that can be considered: external and internal gears. External bevel gears conform to a pitch-cone-angle within the range 0° ÷ 90° (Figure 1 on the left). Internal bevel gears instead conform to a pitch-cone-angle within the range 90° ÷ 180° (Figure 1 on the right).

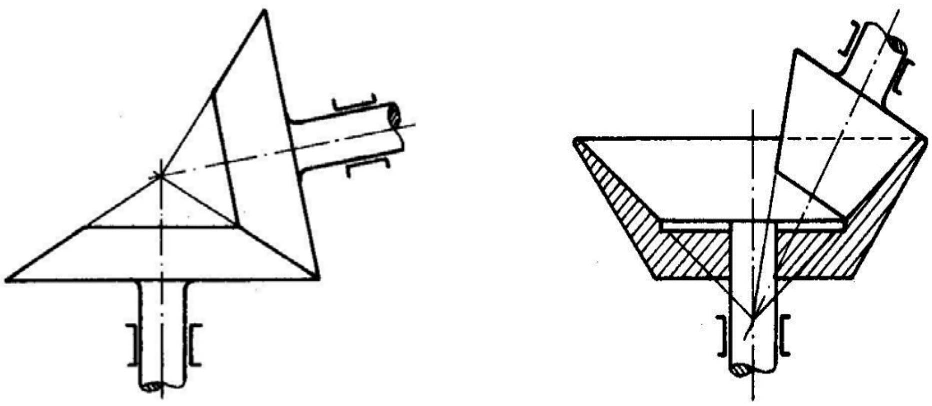

FIGURE 1: EXTERNAL (LEFT) AND INTERNAL (RIGHT) BEVEL GEARS

Bevel gears are conical in shape. They fall into two general groups when viewed in the pitch plane: straight-tooth gears or curved-tooth gears. When viewed in the transverse plane, bevel gears fall into two other groups: generated gears or non-generated gears.

Straight bevel gears (see Figure 2) are the simplest of all bevel gears. The tooth centreline is straight, and if it were extended inward, it would intersect the axis of the work piece. The centreline is a section of the pitch cone element.

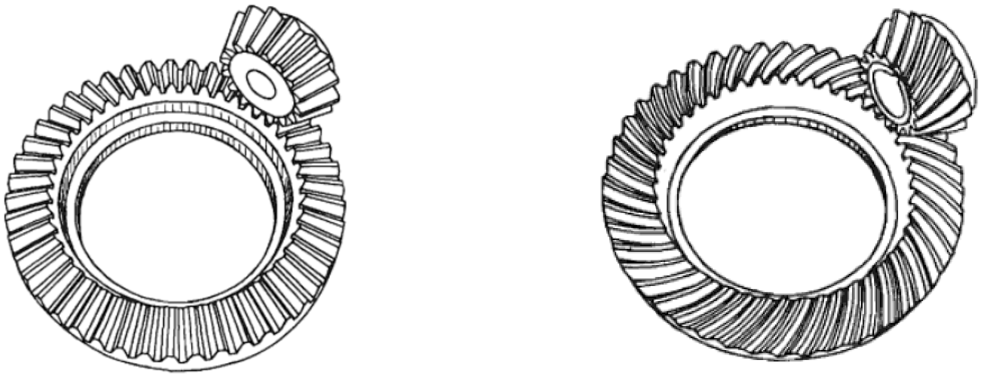

FIGURE 2: STRAIGHT BEVEL GEAR PAIR (LEFT) AND CURVED-TOOTH HYPOID GEARS (RIGHT)

The external bevel gear that are most commonly used in current transmission systems have gear teeth whose active faces conform with an involute approximation. The internal bevel gears are the most complex type of gears and are used to transmit the rotational motion between angularly crossed shafts. Any utilization of an internal bevel gear for transmission purposes requires it to mesh with a companion external bevel gear, but the machining of an internal bevel gear tooth form that is conjugate to that of the external bevel appears to be intractable.

Even though internal bevel gears could be manufactured by using casting or moulding techniques and related materials (e.g., cast iron, aluminium, technical polymers, etc.) there are very few applications of these devices. A machined external bevel gear can be used as a pattern with which to impress a mould face for the quantity production of gears by casting, moulding or powder metallurgy techniques.

The Gleason Format gear technique is a particular technique to simplify the production of external bevel gears with spiral bevel teeth, for a better distribution of tooth loading and lower noise generation. It has proved possible to adapt the technique and facilities to the production of a class of internal bevel gears whose requisite pitch-cone-angles are not much greater than 90°. A typical example of a well-proven machined internal bevel gear produced by the Gleason

Format process is the main drive gear for the rotor of the Westland Wessex helicopter, which has a pitch-cone-angle in the neighbourhood of 100°.

2.1.2 Standard production methods for bevel gears

Most bevel gears generating machines are designed to the basic configuration illustrated in Figure 3. The cutting tools are held by the cradle mechanism of the machine, and the blank is mounted to the work head. Machine adjustments permit proper positioning of the cutter and blank in reference to each other.

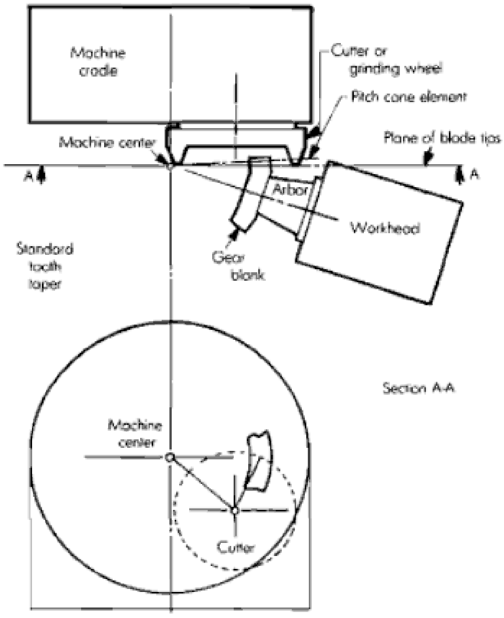

FIGURE 3: BASIC CONFIGURATION OF MACHINE FOR GENERATING BEVEL GEARS

Generating, the basic process, is achieved with straight-sided tools which simulate an imaginary crown gear. During generation, the cutter is revolved about the axis of the cradle. The cradle is rotated at the proper rate of roll relative to the blank, which is simultaneously rotated about its axis. This rolling motion combined with the movement of the cutter along the length of the tooth produces the desired profile shape.

This approach can be used both to cut straight (Figure 4 on the left) and spiral bevel gears (Figure 4 on the right).

FIGURE 4: STRAIGHT (LEFT) AND SPIRAL (RIGHT) BEVEL GEAR PRODUCTION

Another option for producing straight bevel gears is generating them with two tools. Changes in tool thickness are made by adjusting the machine settings, and a set of tools covers a range of tooth numbers and ratios. The method consists of using two tools carried on reciprocating slides. The tools straddle the tooth and cut on each side. End relief, used in Coniflex straight bevel gears, is produced by the slide of the mechanism.

The concept employs two circular interlocking cutters which cut on either side of the tooth space (see Figure 5). End relief of Coniflex gears results from the geometry of the cutter, and the cutters are not moved along the root line. The cutters thus produce a curved root which is slightly deeper than standard at the centre of the face width.

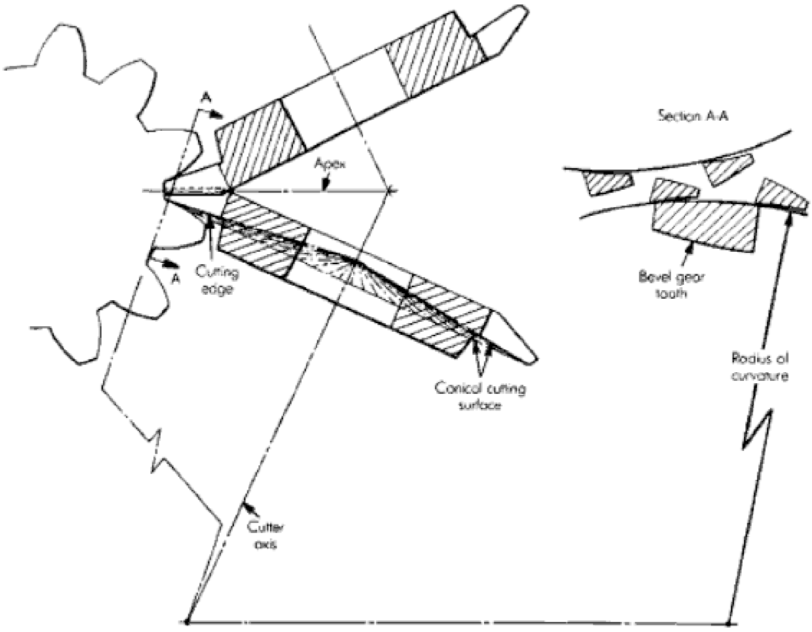

FIGURE 5: CIRCULAR INTERLOCKING CUTTERS CUT ON EITHER SIDE OF TOOTH SPACE

This method is used to produce straight bevel gears, as shown in Figure 6.

FIGURE 6: PRODUCTION OF A STRAIGHT BEVEL GEAR WITH TWO CUTTING DISKS

2.2 STATE OF THE ART OF THE NUGEAR MANUFACTURING PROCESS

STAM has developed the NUGEAR system for space applications. The Nugear can be designed in two different architectures, named “single face” (Figure 7) and “double face” (Figure 8).

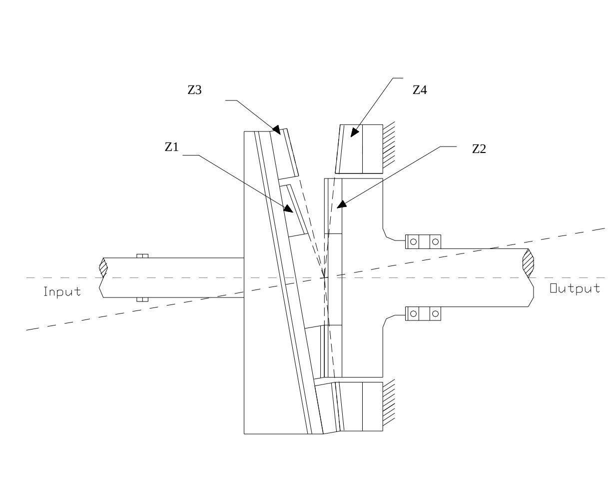

FIGURE 7: NUGEAR WITH “SINGLE FACE” CONFIGURATION

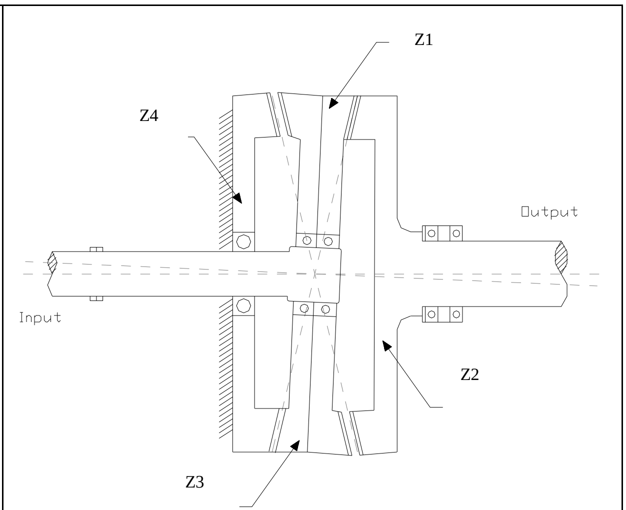

FIGURE 8: NUGEAR WITH “DOUBLE FACE” CONFIGURATION

The main difference between the two configurations is the geometry of the planet link:

- In the “single face” solution the teeth of the two gears on such a link lie on the same side of the link and, therefore, in some way, must be inserted one inside the other (Figure 9).
- In the “double face” configuration the gears are on the opposite sides of the planet (Figure 10), so the two gears may have similar values of the tooth diameters for similar numbers of teeth.

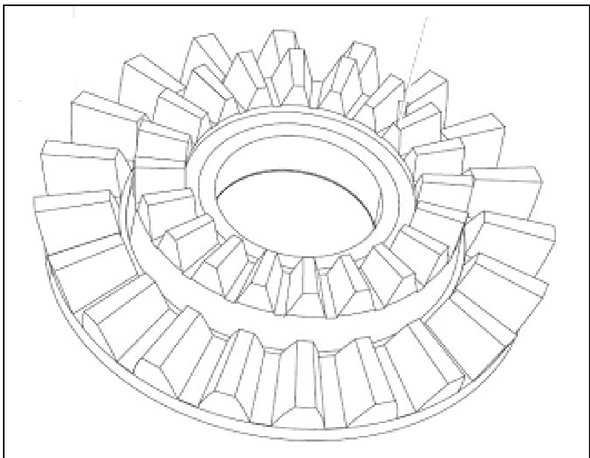

FIGURE 9: TYPICAL PLANET GEAR GEOMETRY OF A “SINGLE FACE” NUGEAR

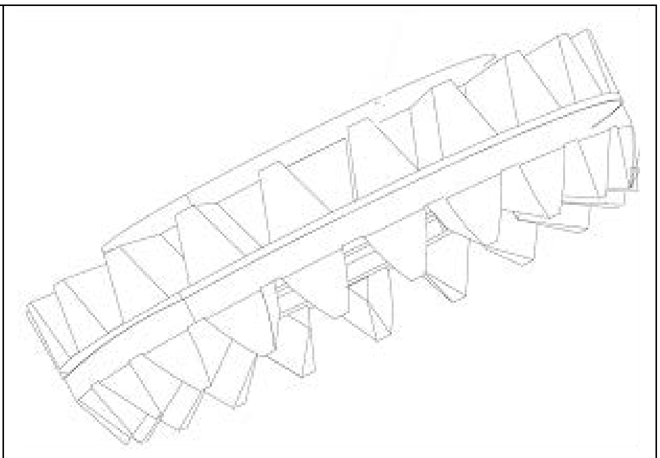

FIGURE 10: TYPICAL PLANET GEAR GEOMETRY OF A “DOUBLE FACE” NUGEAR

This variation affects significantly the architecture of the speed reducer in terms of capacity of load carrying, bearing location, static and dynamic balancing.

Because of kinematical constraints, the “double face” planet link compels designers to use an “internal bevel gear”, i.e., a bevel gear with pitch cone angle larger than 90°. This constraint strongly affects the manufacturing cost of NUGEAR, because manufacturing processes suitable for standard bevel gears are not suitable to produce internal bevel gears.

As a matter of fact, at present, the NUGEAR manufacturing problem was solved using the spark erosion technique (EDM) or CNC milling.

2.2.1 Electrical Discharge Machining

Such technique is suitable for space applications, where the mission cost can justify the high manufacturing cost of the single components, but not suited for large series.

The EDM technology was selected, because of the high precision and the possibility of machining all types of conductive materials of any hardness. EDM is a controlled metal-removal process, which is used to remove metal by means of electric spark erosion. With the EDM process, both the work piece (the gear in our case) and the electrode material must be conductors of electricity.

Two variations exist: dye sinking EDM and wire cutting EDM. In dye sinking EDM a pre-shaped electrode, usually made from graphite or copper (but also brass and tungsten are commonly used), is shaped to the form of the cavity to be reproduced. The electrode is fed down into the work piece and an electric spark is used to cut the work piece, which takes the reverse shape of the electrode. Both the electrode and the work piece are submerged in a dielectric fluid, which can be lubricating oil or, more commonly, dielectric water.

The wire cutting EDM uses as electrode a continuous travelling wire under tension. The electrode travels continuously from a supply spool to a take-up spool, so that it is constantly being renewed. Figure 11 provides a schematic view of the two EDM techniques.

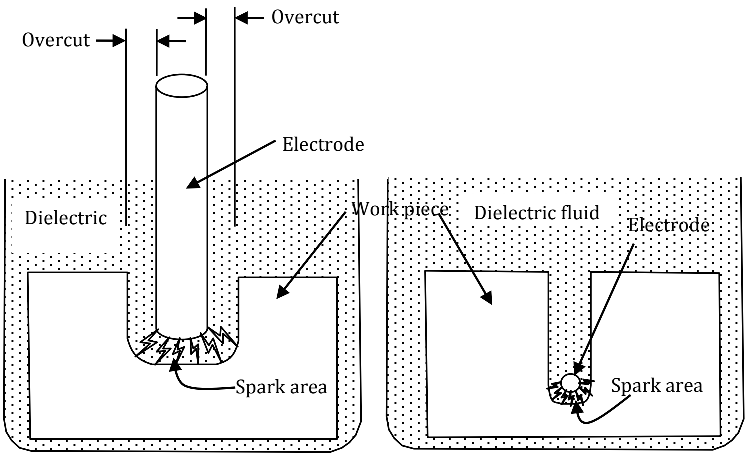

FIGURE 11: SCHEMATIC VIEW OF DYE SINKING EDM (LEFT) AND WIRE CUTTING EDM (RIGHT)

EDM does not produce a completely smooth surface finish. In order to address this issue, copper electrodes have been used (no-wear EDM), in order to minimize tool wear of the base material. Also additives have been used mixed to the dielectric fluid for a more diffuse spark erosion. A proper gap distance between the electrode and the work piece machined surface produced by sparking was considered when designing the electrode, in order to achieve the required final dimensions. Finally, a round orbital movement of the electrode was used, in order to assist in chip removal and allow free flow of the fluid out of the sparking area.

The used technique was based on the manufacturing of the electrodes, shaped like the tooth counterpart, by wire EDM and the gears' teeth manufactured by dye sinking EDM. So bevel gears were manufactured by EDM according to the following manufacturing steps (see Figure 12):

1. the tooth profile is defined according to the CAD of the gears;
2. the electrodes are manufactured in copper by wire erosion;

3. the teeth of the gears are made by dye sinking EDM on the steel blanks + orbital movement of the electrodes for good surface finishing.

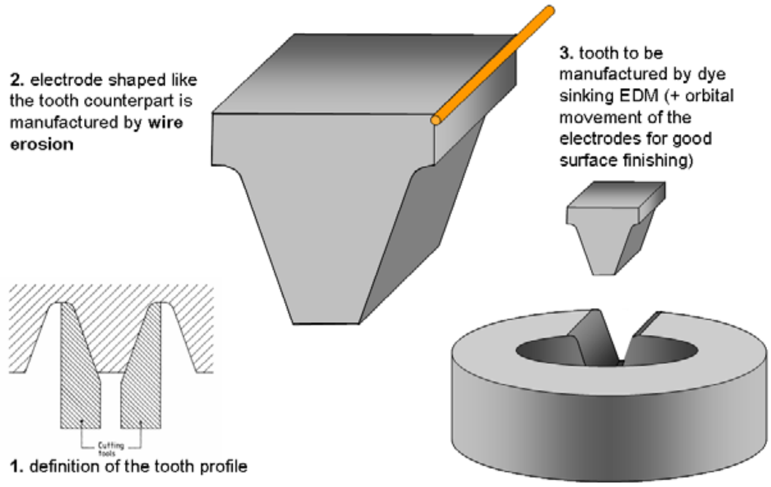

FIGURE 12: MANUFACTURING STEPS FOR THE PROTOTYPING OF THE BEVEL GEARS

Initially, the electrodes were moved downward towards the work piece, but this resulted in a very bad quality of the surface at the bottom of the tooth, as well as excessive erosion of the tooth tip, due to the limited space for discharge of the material at the tip of the electrode. The final approach for the gears manufacturing was based on a radial movement of the electrode towards the centre of the work piece, and the result was very satisfactory.

Figure 13 shows one of the gears in the mechanism, with 20 teeth, and output shaft, before and after the manufacturing of the teeth.

FIGURE 13: PROTOTYPE OF A BEVEL GEAR PRODUCED BY EDM

A common limitation of EDM, which in our case was an advantage, is related to the fact that work hardening may occur during machining. This results in a harder surface layer, which is beneficial for the intended application (micro-gears).

2.2.2 CNC milling

The technology aims at the manufacture of bevel gears using milling machines, with dedicated software that forces the tool to follow extremely accurate paths, optimized for maximum productivity (Figure 14).

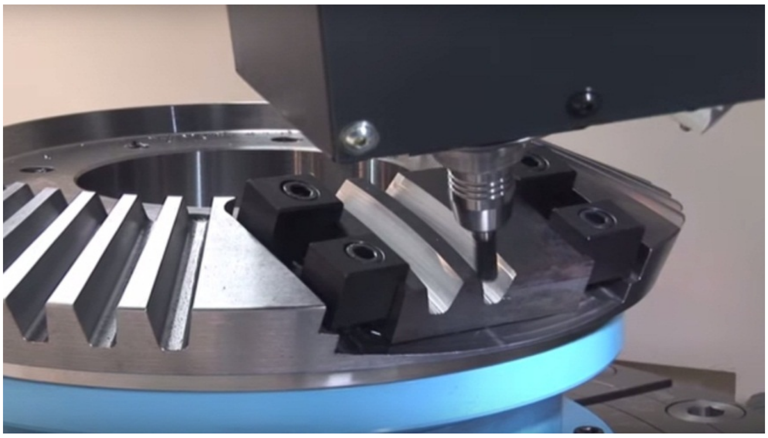

FIGURE 14: GEAR MANUFACTURING BY MEANS OF A 5-AXES MILL FOLLOWING AN ACCURATE 3D PATH

The advantage of this system is that the tip of the tool does the roughing operation, while the portion above the tip of the same tool does finishing of the profile, by removing a minute portion of material left behind in the previous pass, by the tip of the tool. This is possible due to the involute profile of the bevel gear teeth. Moreover, by simultaneously using different parts of the same tool for roughing and finishing operations, the cycle time is reduced.

Also, a slight amount of wear that typically occurs on the tip of the cutter does not affect the profile, and similarly, slight errors in the offset of the tool do not affect the profile. The tool path is directly generated using a CAM post-processor on a 3D CAD. Since there is no need for any special tooling or cutters (all that is required is a standard spherical mill), this is an ideal method to manufacture prototypes or small / medium batches.

The 3D model of the gear can either be used as input for:

1) Approach with mathematical exact calculation of toolpaths for 5-axis free form milling.
2) The use of CAD/CAM approach in combination with extremely small mills (Figure 15).

FIGURE 15: ONE OF THE SPHERICAL MILLS USED FOR THE BEVEL GEARS MANUFACTURING

The first approach can be used for gears with pitch 6.28 mm (i.e. module 2 mm) and higher, while the CAD/CAM approach can be used for all sizes of bevel gears.

The geometry of external bevel gears is calculated according to the drawing data using the software. This geometry is built up from a large amount of points in space which together form a point cloud of the gear. This point cloud is the input for the software.

In this software the operator has to input also the parameters of the mills (diameter of the tools used to rough, pre-mill, finish the part), the extension, the milling direction, the material allowance in pre-milling, etc.

This results in a Numerical Code (NC-code) for the specified 5-axis milling station in the suitable machine language. The NC-code lets the machine move with 5-axis simultaneous movements.

In theory the geometry of the internal gears could be solved by the use of a mirror when computing the tooth surface. In this way an external bevel gear becomes an internal bevel gear. However, special attention must be paid to the geometry of the tooth root, which differs slightly from an external gear.

The geometry of internal bevel gears can be calculated from the drawing data using the software first to calculate a negative model. This means that an external bevel gear has to be calculated, which in fact is a “negative” geometry of the internal bevel gear. This model has to be inverted into an internal gear; for this purpose standard 3D software may be used.

Unfortunately, every attempt to follow this method produced a 3D model for which the software cannot be used, so the CAD/CAM approach in combination with extremely small mills for tiny products was used.

The internal bevel gear geometry was calculated using software, based on input variables taken from the drawings, processed into a 3D model of the bevel gear. This model is used as input for a CAD/CAM, which results in a NC-code for a specified 3-, 4- or 5-axis milling station in the suitable machine language. The NC-code normally uses only 3 axes simultaneously.

An example of internal and external bevel gears produced by CNC milling is shown in Figure 16.

FIGURE 16: THE NUTATING LINK WITH TWO BEVEL GEARS, ONE OF WHICH IS INTERNAL (LEFT)

3 INJECTION MOULD USE CASE

The aim of this chapter is to describe the state of the art techniques used to manufacture an injection mould, such as the one depicted in Figure 17.

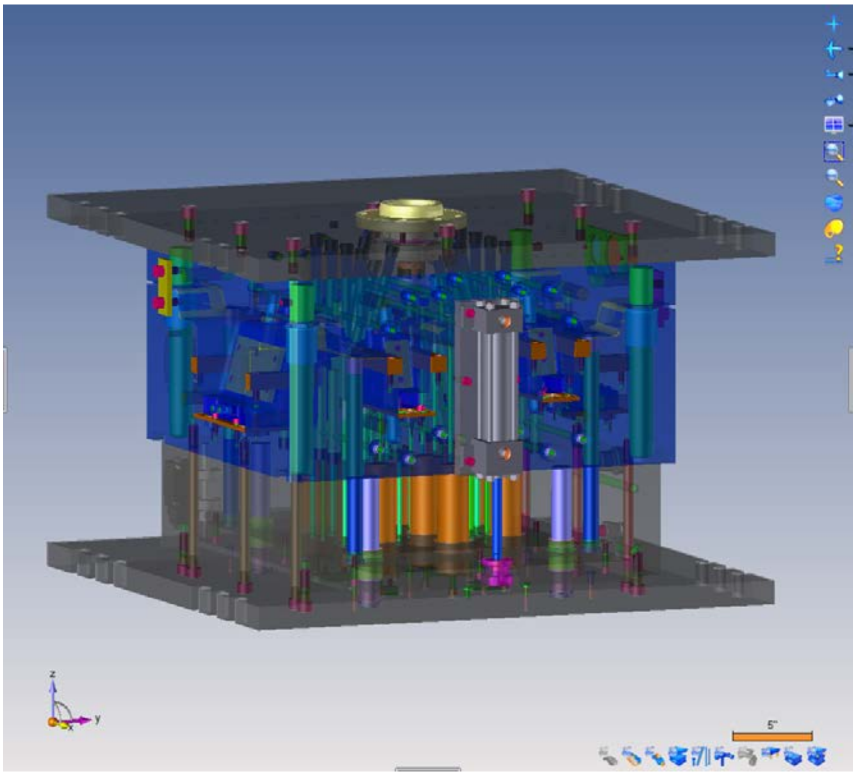

FIGURE 17: DESIGN OF AN INJECTION MOULD

3.1 INJECTION MOULDS AND THEIR MANUFACTURING

3.1.1 Introduction

An injection mould is the core of the thermoplastic injection technology. As shown in Figure 18, the clamping unit with moving platen takes half of the mould. This opens and closes the mould and supplies sufficient force to keep the mould closed when molten plastic is injected under pressure.

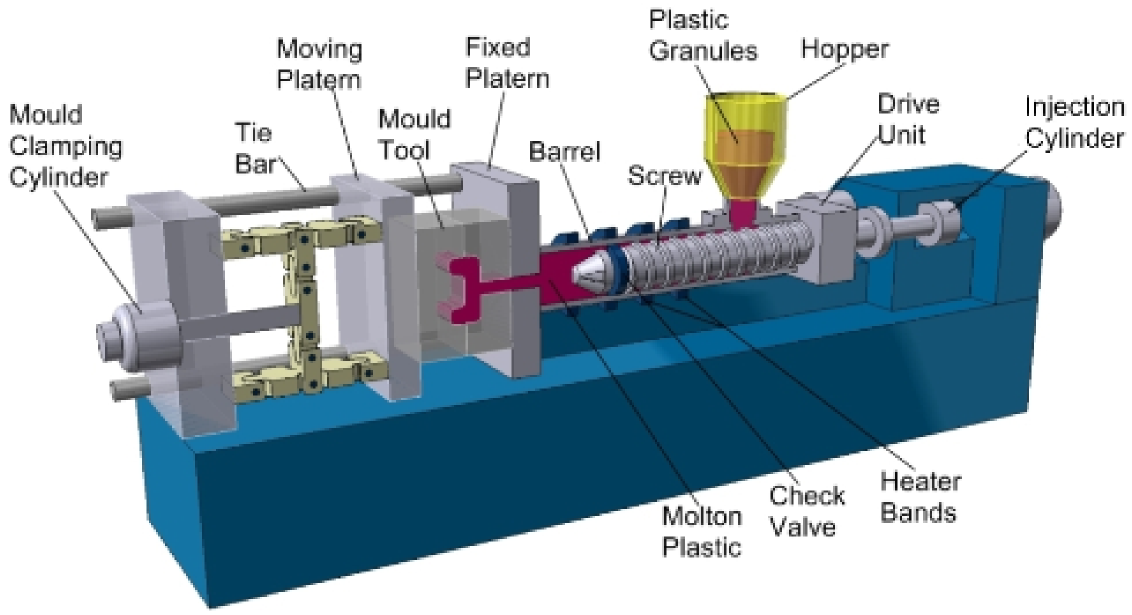

FIGURE 18: EXAMPLE OF AN INJECTION PRESS MACHINE

The injection unit takes plastic raw material granules, heats them until molten, and injects them into the mould. Machines have a barrel that contains a screw (quite similar to a kitchen mixer); the barrel has heater bands around the outside, which raise the temperature to the correct level to melt the plastic.

This needs accurate control, as different polymers have different melting temperatures. If the temperature is too low for the particular polymer, then not all the material will melt; this will result in un-melted pieces of plastic being in the moulding, affecting performance and appearance. On the other hand, setting temperatures too high could result in the plastic degrading, leading to poor appearance and reduced performance. The amount of time that the material resides in the barrel can also lead to degradation, so weight of the part and cycle time become important factors.

The rotating screw forces the plastic along the barrel. This in turn forces the screw back as the molten material collects at the end of the screw. When the right amount of material for the next shot has accumulated, the screw stops rotating. The screw then acts like a plunger moving forward and forcing the molten plastic into the mould.

3.1.2 Mould description

A mould can be divided into five main functions (see Figure 19).

- F1 is the cavity. This affects how the part is moulded and how many parts are moulded in one shot.
- F2 is the injection. This affects how and where the part will be injected.
- F3 is the ejection. This affects how the part will be ejected.
- F4 is the cooling system. This affects how the part will be cooled and the quality of the final result.
- F5 is the frame structure. This affects how the frame will surround the other components.

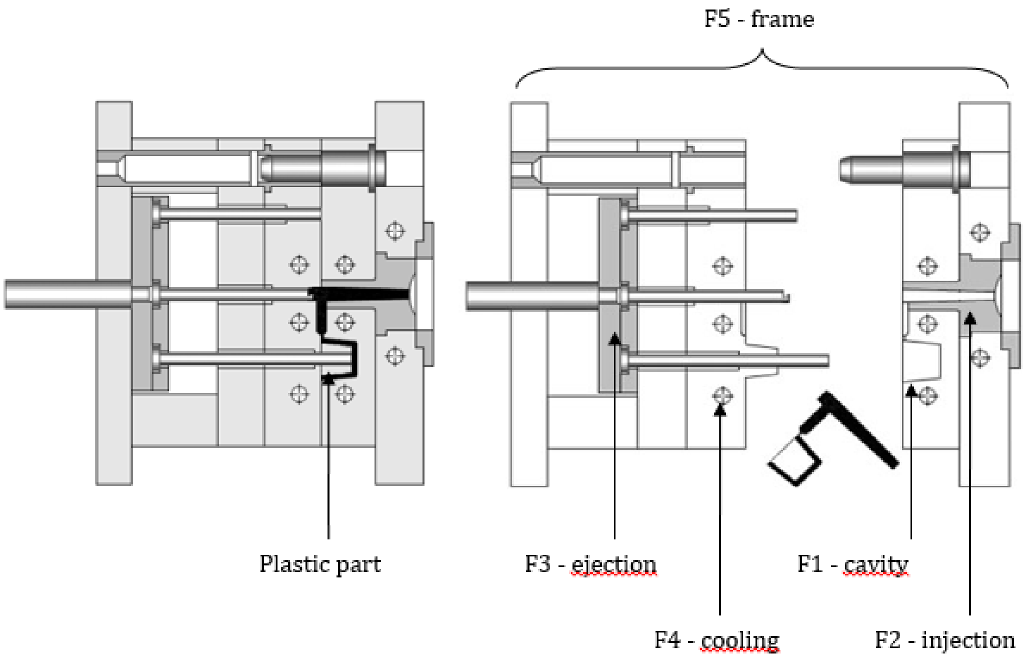

FIGURE 19: FIVE MAIN COMPONENTS OF A MOULD

After being melted into the barrel, the hot polymer is injected into the mould through the nozzle (F2 in Figure 19). The plastic must be kept hot enough in order to fill the cavity (F1) as quickly as possible.

As soon as the cavity is completely filled, the part must be cooled to reduce the temperature, approximately to 60°C; this is done by pumping a cooling liquid in the channels (F4). Then the mould can be opened and the part ejected by the ejectors set (F3).

The cavity is the core of the injection mould: it decides how the part is moulded and of course its final shape.

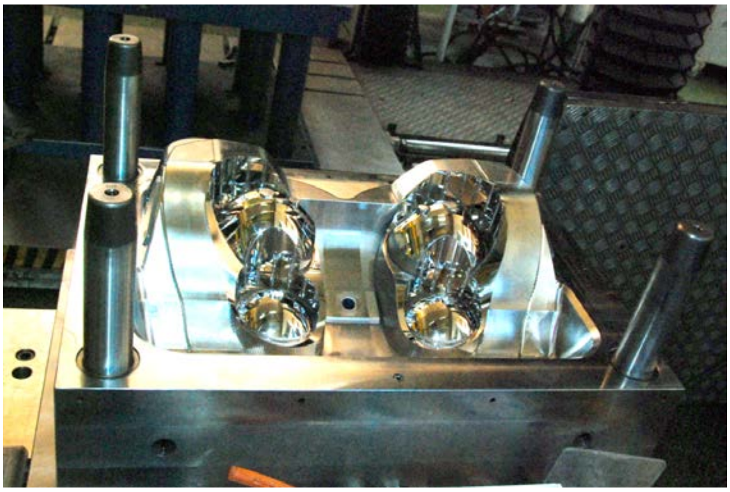

FIGURE 20: EXAMPLE OF A MOULD CAVITY

An important aspect in a cavity is the main moulding direction and the other ones. For instance, if a simple glass must be moulded (Figure 21 on the left), there is only one direction; but if a box

with a hole on the side is moulded (Figure 21 on the right), then there will be two moulding directions.

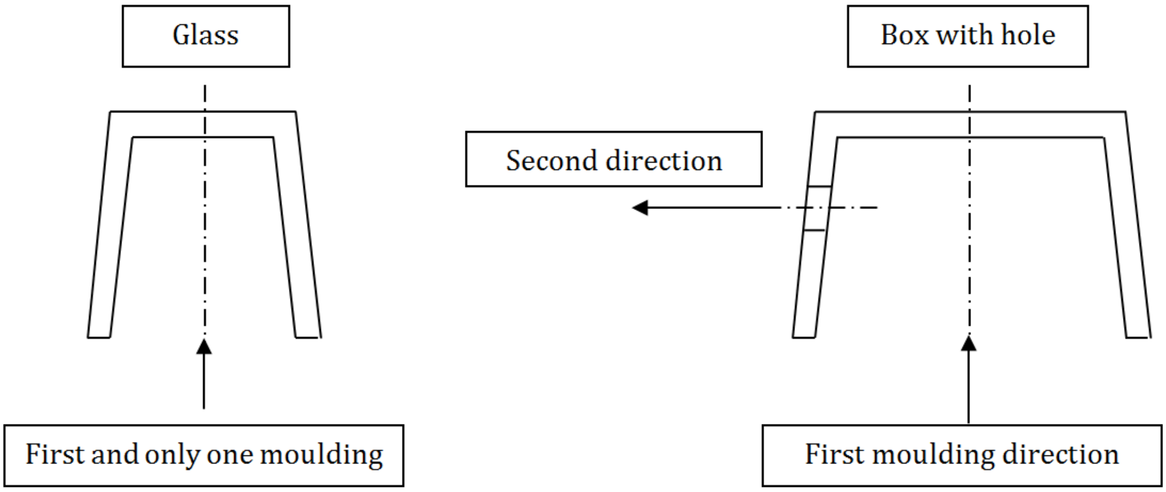

FIGURE 21: DIFFERENT MOULDING DIRECTIONS

When the best way to mould the part is found, the cavity can be designed around the part. In case of a multi-cavities mould, one big cavity can include two shapes, to produce two identical parts.

3.2 TRADITIONAL MANUFACTURING PROCESS OF A MOULD

The traditional method to manufacture a mould is by material removal. The process starts from a block of steel and all the material in excess is removed.

In the following, the main technologies available to manufacture a mould by means of subtractive production processes are described.

3.2.1 Milling

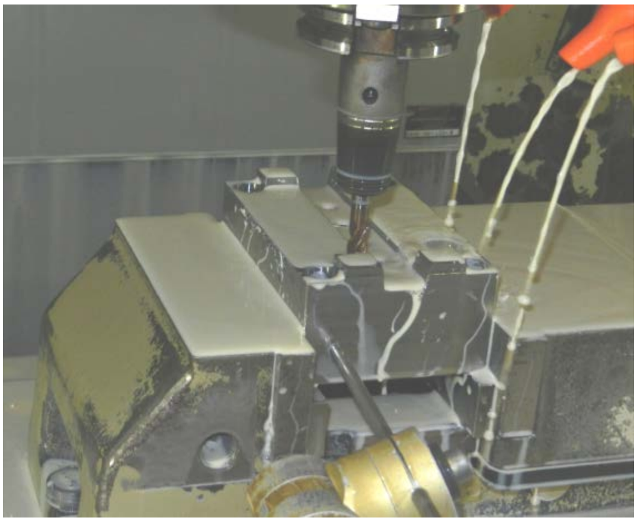

FIGURE 22: MILLING OPERATION

In milling operations (Figure 22) the tool mills the steel. The toolpath is directed by a program generated on a CAD/CAM System. Today, the milling machines can have up to 5 independent axes.

In milling operations the tool is turning about its axis and is moved by the machine axes, while the part is only moving.

3.2.2 Turning

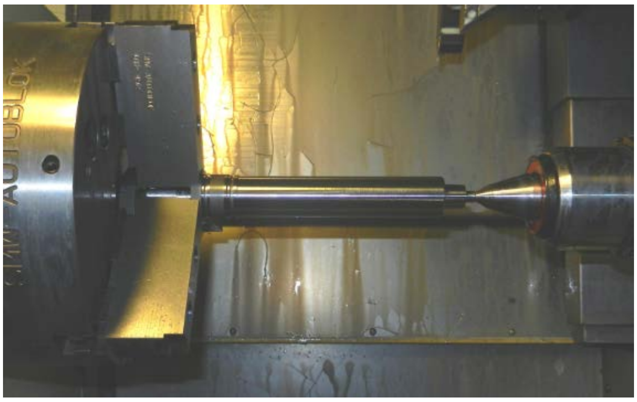

FIGURE 23: TURNING OF A MOULD PART

In turning operations (Figure 23) the tool cuts the steel. The toolpath is directed by a program generated on a CAD/CAM system. Today, the milling machines can have up to 5 independent axes.

In turning operations the tool is moving only and the part is turning about one main axis.

3.2.3 Grinding

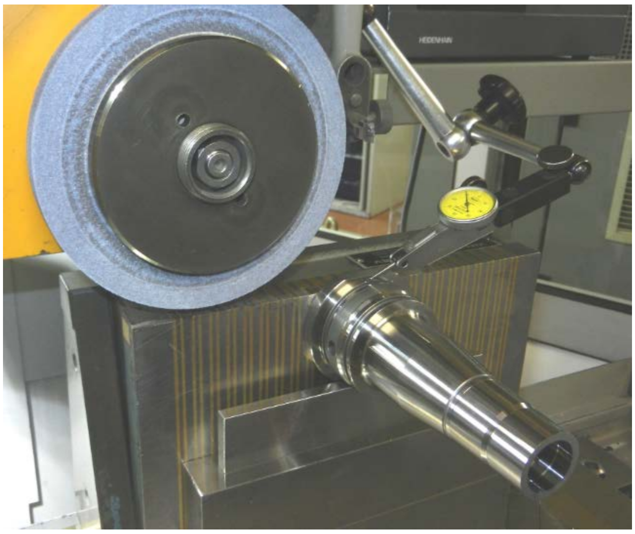

FIGURE 24: GRINDING MACHINE

In grinding machines (Figure 24) the tool is made of stone and grinds the steel part. The toolpath is directly done on the machine.

Both the tool and the part can move and turn.

3.2.4 Electrical Discharge Machining

In EDM (Figure 25) the tool is made of copper and has a negative tension applied by a generator. The steel part has a positive tension applied by the same generator. When the tool is placed near the steel, a discharge occurs and the part is “damaged”, i.e., a little portion of steel is removed.

FIGURE 25: EDM APPARATUS

The tool can also be a copper wire and cut the part. In this case the machine is called wire cutting machine.

4 AM REQUIREMENTS FOR MACHINING

4.1 STAM REQUIREMENTS

STAM's main expectation is to develop an industrial manufacturing process capable to reduce the cost of main components of the NUGEAR; this may lead to the successful development of the overall system. STAM is strongly motivated to work on AM technologies to produce the NUGEAR. In fact the technology could be an interesting way to solve the cost bottleneck related to its commercial exploitation.

Another very important aspect could be to develop an appropriate design for manufacturing, in order both to perfectly balance the dynamic effects of unbalanced masses, without raising production costs related to the production of complex shapes.

In fact, the two components that are characterized by being very difficult to manufacture are the input shaft, where the balancing mass is installed (Figure 26), and the internal bevel gears (Figure 16).

FIGURE 26: INPUT SHAFT OF THE NUGEAR WITH BALANCING MASS

The reduction of component cost is not the only benefit of AM. For different added value applications, such as for the robotic field, the NUGEAR's intrinsic characteristics of multiple teeth engagement could be stressed, as it guarantees high shock/overload tolerance and high reliability. This aspect could be further improved with a proper optimization of the mechanical characteristics of the teeth, by optimizing their shape for instance. In fact, with conventional manufacturing methods the shape of the teeth cannot be modified, while additive manufacturing allows production of free form parts.

To summarize, the main requirements of STAM in the AM are:

- Reduction of the cost of parts (through a more cost-effective process, through manufacturing steps reduction, through the avoidance of specific tooling)
- Reduction of manufacturing time
- Reduction of the weight of parts
- Increase of efficiency of the gears (through reduced surface roughness)

4.2 INJECTION MOULD REQUIREMENTS

4.2.1 Surfaces to be manufactured by subtractive methods

To make the mould can work at its best, some surfaces have to be perfectly realised. It seems evident that all surfaces in contact with the plastic material have to be machined correctly, according to the specification of the definition of the part we want to produce.

In some cases it is necessary to polish all the faces of the cavity, in respect of the visual aspect of this part. The plastic material reproduces the exact aspect of the cavity and all defaults can be visible on the injected part. As an example, a polished surface of a cavity with a simple scratch generates an injected part containing this fault.

The AM process will produce surfaces that cannot be polished, and some accuracy issues may arise as well. A subtractive operation has to be applied to get a perfect result.

Another type of default that can be found in a plastic part is when a mould is not perfectly closed: the component will look like the one shown in Figure 27.

FIGURE 27: DEFECTED PART DUE TO IMPERFECT CLOSURE OF THE MOULD

This could happen when two or more surfaces of the cavity are not perfectly joined. A finishing operation will be necessary to solve this problem, and this need is especially felt if the surface finish is not perfect, such as in the AM case.

The kinematics of the mould can also be really complex. If the plastic part is designed with undercut areas, the mould designer has to define movements to ensure that the part can be ejected.

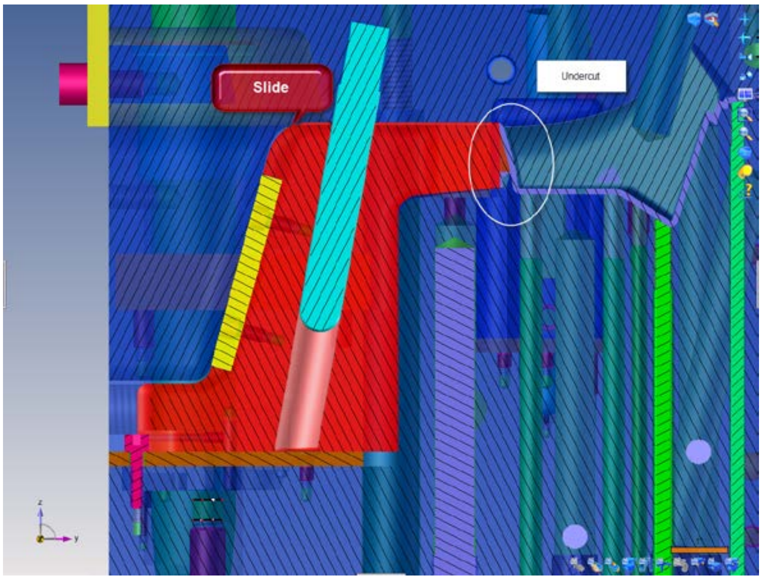

FIGURE 28: SLIDE AND UNDERCUT ON A PART TO BE MOULDED

In Figure 28 we can see the undercut on the part. The slide (coloured in red) slides on its guide pin (coloured in cyan) when the mould opens (as shown in Figure 29).

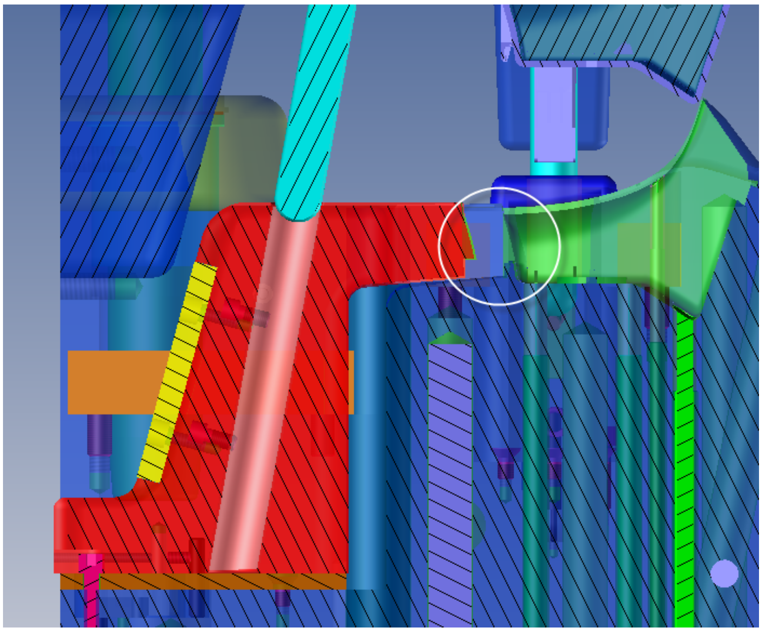

FIGURE 29: OPEN MOULD

All surfaces in contact with the slide or other parts of the movement must be machined to get a good kinematics of the mould. This aspect becomes crucial because of the non-optimal roughness of surfaces produced by AM.

To summarise, the subtractive approaches will be applied mostly on the surfaces defining the part to inject, the parting surface to correctly close the mould, and to all the surfaces necessary to allow smooth movements of the mould itself.

4.2.2 Stock definition

One of the greatest advantages of the AM coupled to Subtractive Manufacturing is that a lot of material is saved, because only a finishing operation is required to achieve a good result.

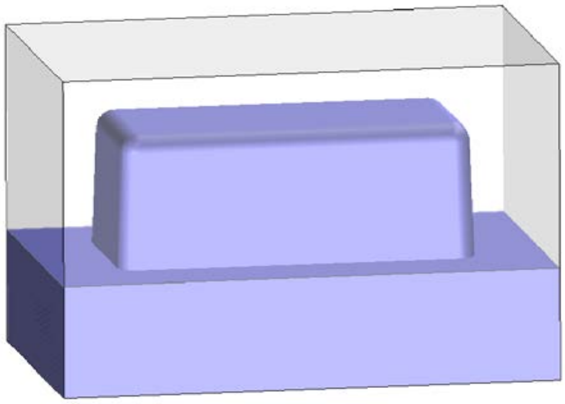

FIGURE 30: EXAMPLE GEOMETRY OF A MALE INSERT

With standard production methods, to manufacture a male insert like the one shown in Figure 30, the process starts with a block of steel bigger than the final part. Then the material is removed all around, until the final shape is reached.

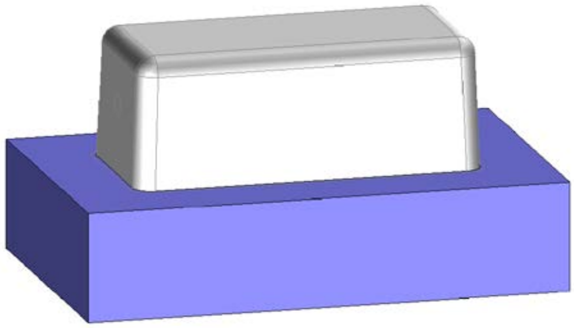

FIGURE 31: MALE INSERT GEOMETRY DESIGNED TO BE PRODUCED BY AM

With AM techniques, to manufacture the same part as above only the part in purple must be milled and welded to the other part in white on it, as shown in Figure 31. Besides, thanks to the AM technology, much more complex shapes can be designed.

Before generating the toolpath for subtractive manufacturing, some operations have to be performed, in order to prepare the part to manufacture. All surfaces that have to be machined need to be offset in the CAD application: this offset will be the “stock definition” of the part. The amount of extra material to be added on the part will be defined according to the minimum value needed to perform a finishing operation, which is about 0.5 mm.

5 INTEROPERABILITY

Figure 32 shows the required interaction between WP6 and the other Work Packages with respect to subtractive manufacturing.

- The stock definition of the part to produce will be defined in WP2.
- WP3 will produce the process plan.
- The actual additive manufacturing is performed in WP7 based on the process plan from WP3.
- WP5 performs dimensional controls and sends the information to the CAD/CAM application.
- WP6 applies the subtractive operations on the part to finish it.

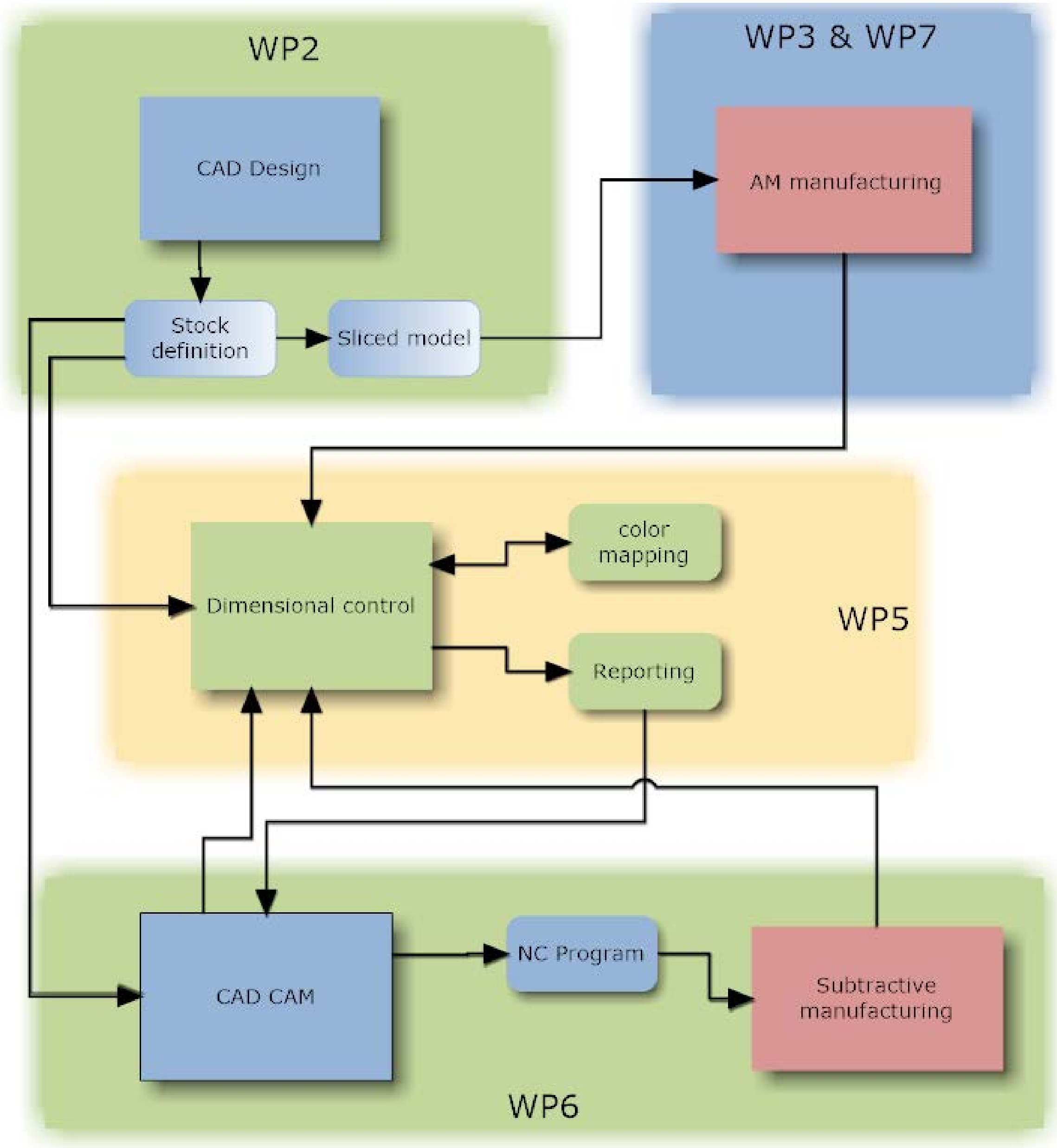

FIGURE 32 : INTEROPERABILITY

6 TERRIFIC APPROACH FOR MACHINING

6.1 INTRODUCTION

In CAD/CAM technologies, objects to be manufactured are usually specified by boundary representations. This description is a collection of faces supported by B-spline parametric surfaces, trimmed by edges supported by parametric curves. It provides a topological and geometrical model of the boundary surface of the object.

In the manufacturing process, this boundary model is used to control the machining tool and to compute the toolpath of the cutting tool. The computation of the toolpath relies on the description of the faces that constitutes the boundary representation. The underlying parameterization of the B-spline surface, which is supporting the face, can be used to guide the cutting tool path in order to obtain high quality shapes. Unfortunately, faces sharing common edges do not necessarily have coherent parameterizations. Therefore, using directly this parameterization is usually possible for machining tools.

The objective of the work developed in the TERRIFIC[2] project is to compute a single B-spline parameterization of a surface for a collection of faces. The iso-parametric curves of this single B-spline parameterization can then be used to compute the paths of the cutting tool. This transformation of a collection of patches into a single B-spline parameterization produces an iso-geometric model.

The aim of this transformation is to improve the quality and efficiency of the machining process. It can also be used in the other applications of iso-geometric analysis such as stress simulation and analysis. As the quality of the resulting product depends heavily on the control of the distance of the cutting tool, the precision of this iso-geometric model compared to the input data is a key issue of this approach. We also take care of the performance of the tool in order to use it in an interactive way in CAD software.

6.2 MACHINING PROBLEM

From the users' viewpoint a CAD-model can naturally be regarded as a collection of objects described by small or large functional surfaces. However, most often in CAD-systems such functional surfaces are split into a patchwork of smaller surfaces patches, where adjacent patches do not match exactly; there are small gaps between the surfaces, which can be a real problem to machine the part correctly and introduce the risk of breakage of the part.

One of the main problems in computing a toolpath from a standard CAD definition is caused by the number of patches describing the topology of the part. With this kind of definition, it becomes really difficult to obtain perfect continuity of this toolpath all along the surfaces to be machined. Tangencies problems might occur, which make the toolpath inconsistent, with extra output like the example below (Figure 33), where some loops are generated by discontinuous patches of surfaces. Moreover, some discontinuities between isocurves from a patch to its neighbours might arise (Figure 34).

[2] FP7-2011-NMP-ICT-FoF-284981, http://www.terrific-project.eu

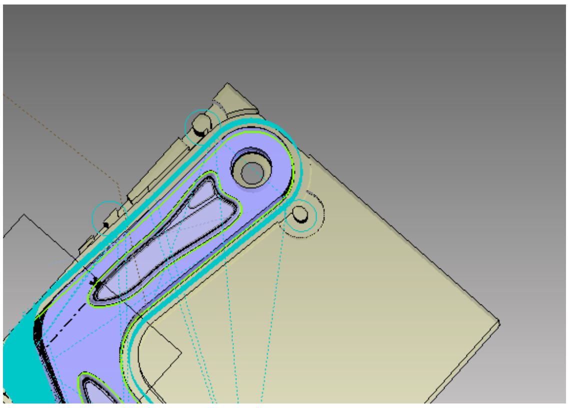

FIGURE 33: DISCONTINUOUS TOOL PATH

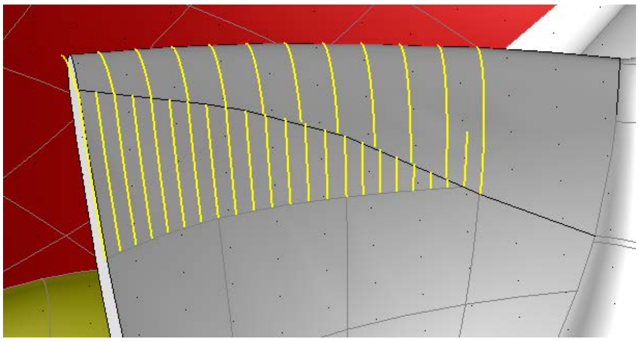

FIGURE 34: ISOCURVES DISCONTINUITY

6.3 IGA APPROACH

To simplify the building of the IGA simulation model, such a surface should be combined with large functional surfaces to allow a flexible block-structuring. TERRIFIC has demonstrated that this IGA-modelling approach is also advantageous in machining to make one surface with perfect tangencies instead of multiple patches of discontinuous surfaces. This approach solves the tangency problems (Figure 35) and allows a perfect continuity of the isocurves all along the surface (Figure 36).

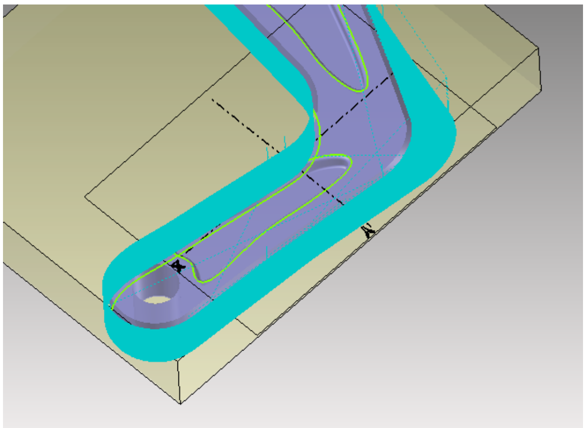

FIGURE 35: TERRIFIC RESULTS WITH PERFECT CONTINUITY OF THE MACHINING

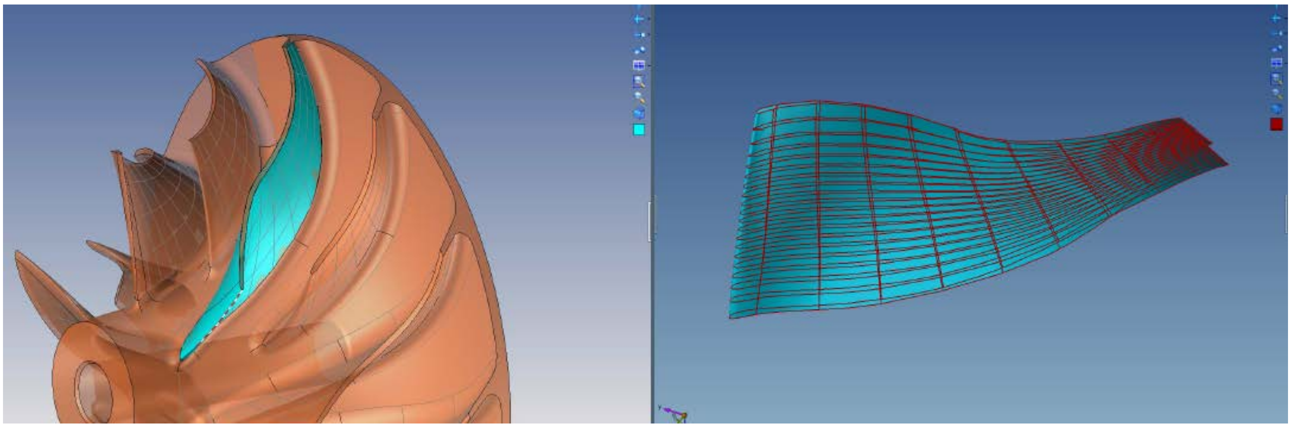

FIGURE 36: CONTINUITY OF THE ISOCURVES

The perfect definition of the isocurves allows applying the toolpath directly on them. This involves less machining time for finishing a part: depending on the size and complexity of the part, gains of up to 10-15% can be reached. Besides, the perfectly continuous and smooth machining implies less wear on the tool and also less breakage of both the tool and the part to be produced. The quality of the machining is considerably improved by using the IGA technology.

6.4 PARAMETERIZATION METHODS

In this section, we describe more precisely the iso-parameterization problem and the new algorithms developed for its solution.

The input of the algorithms is a collection of faces of a boundary representation of the solid. Four edges are identified on these faces, which form a loop. The aim is to compute a B-spline parametric surface with parameters (u, v) in the unit square [0, 1]×[0, 1], which approximates the union of faces within a given tolerance and such that the isoparametric curves u=0, u=1, v=0, v=1 correspond to the four edges.

In a second step, parameters (u, v) in [0, 1]×[0, 1] are computed for each point of the mesh. Several types of methods have been tested:

- Meshed based techniques: by exploiting the neighbourhood of each point of the mesh, discrete coordinate functions u, v are determined from their prescribed values on the boundary curves. Different physical behaviours are exploited: spring model (Tutte method), harmonic functions, mean value, barycentric method.
- Geometric techniques: the points of the mesh are projected onto an initial B-spline surface. For the construction of an initial B-spline surface, Coons patches are also considered.

The third step consists in computing an optimal B-spline parameterization, which fits the mesh points at the corresponding parameters.

- Several error functions are used to determine the optimal B-spline parameterization: point distance function, tangent distance function, and squared distance function.
- To reduce the oscillations of the fitting B-spline surface, a Laplacian term is introduced in this error part, with a small scaling factor.
- The boundary polygonal curves can be fit in a first step and then the interior points of the fitting surface or the points can be fit globally.

The number of spline basis functions is increased in each direction if the fitting error is not below a given threshold and the fitting step is repeated (until a maximum number of iterations are reached).

Once a first B-spline parameterization has been obtained, the second step with the geometric parameterization technique can also be repeated to improve the parameters of the mesh points and the fitting error.

7 CONCLUSIONS

In this document, the main requirements for the development of subtractive machining techniques to be coupled with AM methods in CAxMan project are presented.

The analysis of these subtractive methods related to the AM process and results is mainly focused on the two use cases of the project, i.e., NUGEAR and injection moulds.

Concerning the NUGEAR bevel gearbox production issues, the present high production cost is underlined, representing the main bottleneck towards the exploitation of this component on the large-scale market. Therefore, the first requirement individuated by STAM for this use case is reduction of its components production costs. In addition to costs, time production is aimed to be reduced too. Furthermore, part design aspects are involved in the requirements definition, because an appropriate mass balance and reduction can avoid the need to manufacture complex and not cost-effective shapes in the components. Also improving mechanical performance and reliability, through the surface roughness reduction, is an important requirement for NUGEAR.

Regarding injection moulds, since the quality of the produced plastic part is strongly related to the surface quality of the mould, the first requirement for AM is having a smooth surface after manufacturing. Often, kinematics is necessary in order to eject the plastic part in case of undercut areas: in this case, low metal surface roughness is very important. Another surface quality requirement concerns the perfect adhesion of mould faces, to be obtained when the mould is closed during the plastic casting phase to avoid plastic exiting the mould. Moreover, 3D modelling of injection moulds is expected to consider an appropriate material amount “offset” in the areas to be finished by subtractive techniques.

Iso-geometric analysis technology is proposed, because of its application to surface parameterization. It can help to improve the quality of surfaces manufactured by subtractive methods, sparing up to 15% of machining time and reducing tool wear and manufactured part breakage.