Design Approach for Spiral Milling Parts Using Knowledge Based Engineering

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Abstract. From the engineering point of view there are still problems regarding geometry modelling that cannot be satisfactorily solved despite efficient CAD systems. This applies in particular to virtual models when they are meant to match with the resulting manufacturing geometry of components as closely as possible. In this paper, relationships between modelling and manufacturing strategies are discussed. The focus is directed to the relationship between the modelling strategy and the manufacturing process by spiral milling with a ball cutter, whereby especially the influence of the tool geometry and the tool paths for the modelling strategy will be investigated. By means of an appropriate example of a design of spiral mandrel die from the field of plastics processing an approach will show how functional design and manufacturing-oriented design can be coupled and automated.

1. Introduction
In the field of mechanical engineering problems concerning the design of the 3D model occur in relation to manufacturing. The development process of flow-conducting components, which focuses on the dimensioning of the geometry in the field of fluid mechanics, thermal, and structural mechanics goals, is the relevant example. To reach an appropriate dimensioning, analysis and simulation applications are used. The usage of 3D CAD systems, calculation- and simulation-tools has become the common practice in today's enterprises. The Computer Aided Manufacturing (CAM) technologies are also applied. With this technology manufacturing data can be transferred directly from the virtual product model (3D CAD model). To secure the required quality by the virtual model up to the real part not only a consistent usage of a common data basis (3D CAD model) is essential, but also the implementation of manufacturing information and knowledge in the 3D CAD model. For efficient manufacturing the manufacturing strategy has to be implemented as early as possible during the product development process. For this reason it is necessary to find a reasonable compromise between the optimal, functional design and geometry resulting from the specified manufacturing processes. How can this be realised?
By the use of methods and tools of Knowledge Based Engineering (KBE) both manufacturing process information and manufacturing knowledge can be integrated into the 3D product model (see figure 1).
One useful approach in this case is the Feature Technology. This strategy offers the possibility to find a meaningful compromise between design and manufacturing geometry. This will ensure that the CAD geometry is created according to the required manufacturing steps. Proceeding this way can ensure that the simulation results, which are based on the virtual product model, can be transferred to the manufactured part. Regarding this, the present paper propounds a possible strategy which allows the consideration of manufacturing constraints during the development process of a spiral mandrel die for plastics extrusion.

2. Today's development process of spiral mandrel die

Extrusion is a technology for the continuous manufacturing of semi-finished plastic products, such as pipes or tubes. A spiral mandrel die is a shaping extrusion die which transforms the plastic melt (provided by an extruder) into the product cross section. The quality of a spiral mandrel die has a main influence on the product quality indicators, such as wall thickness distribution, surface characteristics, or mechanical properties. Today, the development process of spiral mandrel dies (see figure 2) is mostly based on the use of empirical knowledge. This manual development approach is usually carried out iteratively, which means that the pre-dimensioned geometry proceeding from the first calculations is iteratively changed until the goals (e. g. uniform flow rate at the die outlet) are reached [1]. The quality of the resulting product is analysed according to the properties as criteria for the wall thickness distribution and maximal and minimal shear stress by conducting Computational Fluid Dynamic simulations (CFD) [2, 3]. Current research activities in this field focus on a complete automation of the development process in order to minimise today's time-consuming, repeatable and manually performed steps [4, 5, 6]. Those available approaches have in common that designed CAD models of the tool have to be transformed into a geometry suitable for manufacturing in each separate step (e. g. milling, turning). Based thereupon it is possible to generate the essential manufacturing documents (drawings, CNC data, etc.). As technical manufacturing restrictions are not usually taken into account during the prior development process further adjustments of the design are usually necessary before the manufacturing data can be generated.
The spiral milling on the 4-axis machine can be applied to the manufacturing of helical flow channels of the spiral mandrel die. The spiral milling, which is the result of the helical feed motion, is also used for worm milling, thread milling and thread whirling [7]. The advantages of this manufacturing method mainly lie mainly in the high productivity, low set-up and tool change times and the easy chips disposal [8]. It is easy to imagine that this strategy is characterised by the presence of an interdisciplinary know-how and great wealth of experience on the part of the design engineer, but also by high costs and time consumption.

3. CAD-based Approach

To generate the accurate geometry of the real spiral milling process in the 3D CAD model using the Feature Technique, a feature is required which corresponds to the spatial movement of solid objects and creates the three-dimensional swept volume in the CAD system. However, present-day CAD systems do not deliver feasible solutions for this problem. Hence Multi Body Simulations (MBS) deliver swept envelope as triangulated volumes, which is not satisfying due to data size and data quality. The focus of the developed approach is based on generating swept tool envelope surfaces, which encloses the swept volume of moving tool. This issue has been investigated before from a mathematical point of view [9, 10, 11, 12]. These approaches mostly define the opportunities for analytical or differential geometric surface descriptions of different surface types. However, these methodologies cannot be applied by the CAD system users because the CAD-internal geometry description is barely adaptable. For this reason a CAD-based approach has been developed which allows the automated generation of swept tool envelope surfaces for the component design by application of KBE methods (see figure 3).

Figure 2. Today’s development process of cylindrical spiral mandrel die
Figure 3. CAD-based coupling approach of the dimensioning, design and manufacturing data

3.1. Virtual Machining Tool and Trace Curves (tool path)
The development process of the spiral mandrel die commences upon dimensioning. Based on the relevant process parameters, the geometry data such as the number and pitch of the spirals, depth profile and width of the spiral channel, the width of the overflow gap and other design details such as radii, chamfers and sealing surfaces can be calculated for the 3D model design of a spiral mandrel die [1]. Here the most important dimensioning design data are the values of the depth profile of the spiral channel. They are represented by the 2D curve, which can be interpreted as an unfold trace curve of a milling cutter (tool path). For the design of the spiral channels in the CAD system the 3D curve is necessary, therefore the 2D curve should be transformed by appropriate methods into 3D representation. Furthermore, its suitability and feasibility for acting as the trace curve of a milling cutter (tool path) on the 4-axis machine has to be verified. For the proper analysis of this concern, the knowledge of the spatial arrangement of the milling cutter and the workpiece as well as of the kinematic chain of the machine tool is primarily important. These conditions and restrictions describe the specific form of the milling cutter motion envelope surface which arises from the tool path during the spiral milling process as well as the primary design data of the extrusion-die. This transfer of the “real” tool motions and cutting geometries into the CAD development process leads to improvements of the initial die design. The description of the tool path can be realised through various approaches, e.g. by analytical geometry description methods or by using MBS.

From the mathematical perspective it is a helical curve, which is often referred to as a helix curve. The general equation is shown in figure 4 (a). On condition that the dimensioning data for the depth profile of the spiral channel are provided or described in the form of coordinate tuples or a mathematical or graphical function, the linking of the data to the analytical description of a 3D curve in the CAD system is easy to realise (see figure 4 (b) and (c)). To secure the spatial definiteness for the modelling of the swept tool envelope surface, a second 3D curve is required to be followed by the cutter tool. In case that during the manufacturing process the cutter tool axis is aligned perpendicularly to the workpiece axis, the analytic description of the second cutter tool trace curve has to be supplemented by the distance “a”. In case that additional rotation by the angle “α” is considered, the analytical description has to be completed by component "b” (see figure 4 (c)).
Figure 4. Analytical description of trace curves (tool path)

Another way to generate the “real” and “feasible” tool path directly without mathematical calculations is the use of trace curves of the MBS. These are 3D curves which can be automatically generated by the CAD systems as simulation results by defining characteristic points on the cutter tool faces and axis. These curves are used for suitable surface modelling and the automated generation of the swept milling cutter envelope surfaces in the subsequent steps of the presented approach (see figure 5). In order to unambiguously integrate the dimensioning data into the simulation the position of the tool’s characteristic points is significant. For the case presented here the first point is defined in the centre of the ball cutter and the second on the ball cutter axis. By setting a course profile in the form of a 2D curve for height control of the cutter tool or for the machine table, which corresponds to the helix depth profile from dimensioning data, the real tool paths can be automatically generated pursuant to the simulation process.

Figure 5. MBS trace curves (tool path)

The difficulty in the creation of the presented “Virtual Machining Tool” based on the MBS is the determination and mapping of the real machine kinematics with the help of virtual joints. They do not necessarily stay in 1:1 relation with the real joint connections. However, the use of the kinematic method is a distinct advantage, because the "accuracy" and "feasibility" of the analytically calculated trace curves from cutter tool can be verified in a simple way.

3.2. Swept Tool Envelope Surface-UDF

Generally, trajectory features are used for the geometry design of such spatial characteristics of manufacturing processes in the CAD systems. They allow the sweeping of a 2D section along one or more trajectory curves (also known as guide curves). In contrast to manufacturing operations, such as
drilling or pocket milling, the spiral milled channels can be depicted for simple exceptions by one single feature in CAD systems (see figure 6). The presented case refers to the manufacturing process on a 4-axis milling machine with helical feed and ball mill as cutter tool. The rotation axis of the cutter can be arranged perpendicularly or obliquely to the workpiece axis. In both cases geometric deviations were obtained compared to the real manufacturing geometry, which is shown by the control sections.

Figure 6. Geometry problems by the design of spiral channels in CAD systems

The cause lies in the fact that depending on how the spatial arrangement of the tool is in relation to the workpiece, a differently complex geometry of the cutting process may result. In order to map a precise manufacturing geometry using a geometry feature in a 3D CAD model it is necessary to provide the possibility of spatial movement of solid objects and creates the three-dimensional swept volume. This is, however, still very problematic in today’s CAD systems or hardly possible. Therefore, another solution approach is needed. Since we are basically dealing with ruled surfaces respectively screw surfaces and their degenerations, a surface-based solution strategy can be applied. For the spiral mandrel die in conjunction with a ball cutter and the spiral milling on a 4-axis machine the ball part of the cutter can be depicted as a swept tube surface. The cylindrical part is formed by a surface offset from the centre area, which is defined as ruled surface along the kinematically or analytically determinated tool guide curves (see figure 7).

Figure 7. Modelling of a swept cutter tool envelope surface

By further surface design operations the surfaces can be merged into a single associated collecting surface and subsequently be subtracted from the solid (blank). Through the use of UDF not only the single modelling steps can thus be combined to generate tool motion envelopes proper to the specific manufacturing and be provided in a database for future use; it also allows the integration of manufacturing-relevant information on to-be-used tools and machine parameters for the subsequent CAM processes.
4. CAD-application for the design of a spiral milling parts

The presented CAD-based approach to design spiral milled 3D CAD models has been exemplary implemented in an application. For this purpose, the Application Programming Interfaces (API) of 3D CAD systems CATIA V5 were used, as well as SolidWorks 2010 and Creo 2.0, in order to develop an application program in Visual Studio 2010 (see figure 8).

With this application it is possible to design a spiral milled channel with a ball cutter in mandrel as well as housing suite to manufacture in the above mentioned 3D CAD systems. Furthermore, it allows to create the 3D CAD models of cylindrical mandrel dies under consideration of dimensioning and simulation aspects. The generation of the tool paths by an analytical or kinematic approach is feasible. For the kinematic approach a sub-program has been developed in conjunction with the CAD system Creo 2.0, which allows the user to configure a virtual manufacturing machine with all relevant parameters. In this application three machining methods (turning, spiral milling, and cutting) have been implemented, so that, motion analysis (MBS) can be performed automatically, depending on the choice of the method, the tool parameters, the position of the tool to the workpiece axis and other process-specific parameters. Thereby it is possible to distinguish between the generation mode as well as verification mode of the tooling process for the spiral milling with a ball cutter. For all the mentioned manufacturing methods the tool- and machine-dependent motion envelopes can be generated as a triangulated volume for further geometry testing.

5. Summary

In this paper a practicable CAD-based geometry design approach for spiral milling parts is presented as well as concrete subjects of the development, design and manufacturing process of a spiral mandrel die for plastics extrusion are discussed. The analysis pointed out a potential problem in transforming the geometry design with the CAD-Systems to the manufacturing geometry using a ball cutter and spiral milling process on a 4-axis machine. On this basis a data coupling approach of the dimensioning, designing and manufacturing has been proposed and an appropriate surface-based
modelling strategy has been developed. The use of KBE methods, such as UDF, in combination with hybrid modelling techniques and rule based model design leads to an improved process. Using this approach, the modelling steps of swept cutter envelope surfaces for spiral milling can be stored in a database for future designs. In addition, the integration of tool and machine parameters for the subsequent CAM processes shortens the subsequent steps and allows a positive influence on the products' costs, quality and on the development- and production time. The developed approach ensures that the virtual geometry of the part corresponds to the “real” geometry generated by the spiral milling manufacturing process. The suitability of this approach is proved by optical measurements of a spiral mandrel die.

6. References
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