A CAD/CAM concept for High Speed Cutting compatible rough machining in die, mould and pattern manufacturing

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Abstract

Die, mould and pattern manufacturing plays a central role in the production of capital and consumer goods. Ever-shorter product life cycles and the expanding diversity of features require continued cuts in production lead times.

Recently, these developments in the market, accompanied by a simultaneous demand for improved quality at a lower cost, are becoming clearly noticeable. Along with the streamlining of organizational structures and advanced technological developments, it is above all the introduction of CAD/CAM software that offers great potential for reducing lead times for components with free surfaces.

The role of milling in the integrated process chain of die, mould and pattern manufacturing is steadily gaining importance. This is due to the ongoing further development of milling-machine technology, the cutting tools and their coatings, and of the CAD/CAM systems themselves. Generally speaking, the milling process is divided into the operations of roughing and finishing. For rough milling, efficient machining means high stock-removal rates together with close contour approximation and low tool wear. Rough milling is normally carried out layer by layer, i.e. in a 2.5D machining operation with constant depth per cut because the rate of material removal and process reliability are usually highest when this method is used. High-speed cutting (HSC), which has been the subject of extensive university research for far more than ten years, has meanwhile become established as a finishing process in many companies. However, the application of HSC demands the observance of geometric and, above all, technological constraints. A considerable degree of optimization can be achieved when these constraints are applied to rough milling.

In the integrated process chain, the CAD/CAM system performs the task of calculating NC programs based on CAD data which meet the requirements posed by rough and finish machining operations. While general interest was focused on the development of CAM strategies for HSC finish machining, advanced development of technology-oriented CAM modules for upstream roughing operations was neglected.

The paper at hand deals with the development of a CAM module for rough-machining complex components in die, mould and pattern manufacturing. It provides an insight into the process-technological demands made on HSC operations and their application in rough machining, from which guidelines and requirements on technologically

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oriented NC functions for CAM software were derived. These encompass both the complete development of an interactive, dialogue-based user guidance function and the algorithmic conversion of the calculation routines. The concept at hand was almost entirely implemented and integrated in the CAD/CAM system developed by Tebis AG, Germany, which was conceived especially for die, mould and pattern manufacturing and is scheduled for introduction to the free market starting in April 2001.

Acknowledgements

Contents

Chapter 1

Introduction

Die, mould and pattern manufacturing plays a central role in the production of capital and consumer goods. Growing demands on quality and ever-tighter cost restraints have created a critical situation in the market that forces the die, mould and pattern sector to streamline planning and production sequences in order to maintain its competitive position in the market. Steadily shrinking product life cycles and the expanding diversity of features require continued cuts in production lead times. In many cases, design considerations and the need to optimise product engineering call for complex part geometries. In the mechanical-design area, this has resulted in the expanding use of free surfaces for product implementation.

Metal-cutting processes play a significant role in the shaping of complex parts. Milling, in particular, makes it possible to produce such geometries cost-effectively. Due to this central function, milling is steadily gaining importance in the integrated process sequence of die, mould and pattern manufacturing. This can also be attributed to continued advancements in milling-machine technology, cutting tools and their coatings, and CAM systems. Achieving the desired results calls for optimum co-ordination of the diverse components of the process as well as organisation of the necessary process know-how.

In this context, computer-aided techniques applied in design (CAD) and manufacturing (CAM) have gained enormous significance. They have made it possible to replace the time- and personnel-intensive tasks which prevailed in these sectors prior to their introduction.

In the early 1970s, CAD meant just what the three letters stood for: computer-aided design. And even if the appearance of 2D line graphics on the screen evoked cries of joy at the time, CAD is a good deal more today. Software that imparts a realistic concept of virtual space to the viewer or displays a designed part in realist photo-like quality, thus obviating the need to build a prototype, has long been in use. Companies who still do not utilise CAD today will therefore become increasingly less competitive in the future. However, today's CAD user in die, mould and pattern manufacturing is confronted with the problem of having to master more and more complex tasks in less and less time. Moreover, in addition to the appropriate CAD system, he or she also requires comprehensive support and the necessary training.

A closer look at computer-aided milling reveals CAM software that essentially consists of an NC programming system. Such systems have become an indispensable part of today's manufacturing companies. Most machine tools used in the metal-cutting industry are equipped with CNC. Since the complex parts must be produced very quickly using such machines, it is no longer possible to create the required NC programs manually. In contrast to conventional manufacturing, in which the operator controls the machine tool, every traversing movement and switching function must be made available to the numerically controlled machine in the form of encoded data, i.e. the NC program. The acquisition of all geometric and production-related information for machining parts on numerically controlled machines is referred to as NC programming. NC programming systems are computer programs that support the user in generating NC control data or even virtually relieve him of this task. In stand-alone NC programming systems, the geometric data of a part are imported via an interface from a CAD system. In the case of integrated CAD/CAM system, the user continues working directly with the previously designed CAD model. The geometric description of the part to be produced, process parameters and the cutting strategy must be defined in interactive dialogue with the system. Based on this information, the NC programming system then generates traverse paths for the cutting tool, whereby the NC system performs the calculations required to determine cutter location. This is followed by a postprocessor run, in which the part program is converted into the specific format required by a given control. The result is the NC program.

In NC milling, the machining procedure is usually divided into three operations: roughing, semi-finishing and finishing. For efficient machining in die, mould and

pattern manufacturing, rough-milling must achieve high stock-removal rates while maintaining good contour approach characteristics and low tool wear. These aims can be accomplished if the selected tools and cutting-tool materials meet the requirements and if toolpaths are appropriately designed. Roughing is usually layer-guided, i.e. performed in a 2.5-axis machining operation with a constant depth of cut, because this method normally achieves the highest rate of metal removal and maximum process reliability. The cutter is guided along horizontal clearing layers while maintaining a constant cutting depth. High cutting capacities can be obtained due to the favourable stock-removal conditions in a purely peripheral cut. A more or less uniform residual offset remains on the part, depending on the geometry of the milling cutter and the selected cutting depth. Cylindrical tools are used most frequently for roughing, leaving the familiar stepped structure after machining. Semi-finishing is normally performed by milling parallel to the end contour with a minimum offset. This offset is gradually reduced until a nearly constant oversize remains across the entire surface structure. In terms of cost-effective and quality-oriented finishing, the aim is to obtain the maximum rate of metal removal while minimising tool wear. Essentially, ball-end mills are used due to good adaptation to the contour.

The most recent major innovation in milling is the introduction of high-speed cutting (HSC). HSC has prevailed as a finishing or semi-finishing process, where it produces better surface finishes by means of narrow step widths. The additional time required for this is compensated primarily by very high feed rates and spindle speeds. Now even filigree contours can be machined, which has sharply reduced the proportion of spark-erosion die-sinking. Due to the excellent surface finishes obtained, the need for manual refinishing has been reduced considerably [11].

One of the most important prerequisites for a reliable and effective HSC operation is a limited but above all constant residual offset, which may be between 0.05 and 0.5 mm, depending on the material and part geometry. This is the only way to control the load exerted on the extremely hard and therefore sensitive tools and cutting-tool materials. But the various reports of success in connection with HSC and the current level of development in CAD/CAM systems neglect the question of how to accomplish suitable pre-machining of parts. Surely one of the reasons for this is that machine requirements for conventional roughing differ sharply from those for finishing and, consequently, require separate consideration. But, because demands on pre-machining

are posed by the finishing step, an overall examination of the process sequence, from cuboid blank to finished part, presents a great potential for increased performance.

The NC programming system must take a range of technological requirements into account in order to generate optimum paths for HSC. In addition to machining-related features, these primarily involve the properties of the machine tool, geometric shape and material of the part, cutting material and geometry of the cutter and, in particular, the milling strategy. Examples such as continuous cutter engagement, uniform feed motion and soft tool travel can be mentioned here. Thus the milling strategy becomes a central element of process technology and therefore of the required machining know-how. If these parameters are not only taken into account for HSC finishing, but applied to roughing as well, performance in that area can also be increased many times over.

However, to exploit this potential the organisation of the roughing operation must take specific metal-cutting requirements into account, in addition to basic geometry-related data, to guarantee the necessary process reliability. But to a large extent, commonly used CAD/CAM systems provide only geometry-related NC functions while neglecting these specific metal-cutting requirements.

The aim of this thesis is to develop a CAD/CAM concept in which the potential for optimisation described above is implemented. For this purpose, the author will elaborate technological process requirements posed on an optimum rough-machining operation with the aid of available knowledge of the HSC process and present solutions for their implementation in a CAD/CAM system.

Chapter 2

Process-related technological fundamentals

2.1   Definitions

In production engineering a distinction is made among pattern, mould and die manu-facturing. A pattern is a replica of the later manufactured part including production-related attachments. A mould represents the negative image of the later finished part. Depending on the material of which the part is made, a distinction can be made among, for example, casting moulds for metal tools, injection moulds for thermoplas-tics and sintering moulds for ceramics. Thus whereas moulds are used for primary forming processes, dies are employed for re-shaping or cutting. Deep-drawing dies, trimming dies and compression moulding dies are all examples of dies.

Milling does not distinguish among processes for manufacturing dies, moulds and patterns. Therefore, patterns, moulds and dies will be referred to in the following by the generic term part.

2.2   Process techniques in milling

2.2.1   Manually controlled milling

Milling is a chip-removing metal-cutting process. Milling originated as an industrial process for machining parts with so-called manually guided milling. Based on a workshop drawing, the geometry of the part is traced onto the upper surface of the blank in the form of horizontal contours. The material is then removed from the blank, layer by layer, with the aid of the scribed lines and templates prepared from the drawing. In the process, the milling cutter is controlled by means of manually operated levers whose movement is converted into a feed motion by mechanical or hydraulic power-transmission equipment (Fig. 2.1).

Production drawing

Scribed line

Template

Geometric data: Scribed line and template from drawing
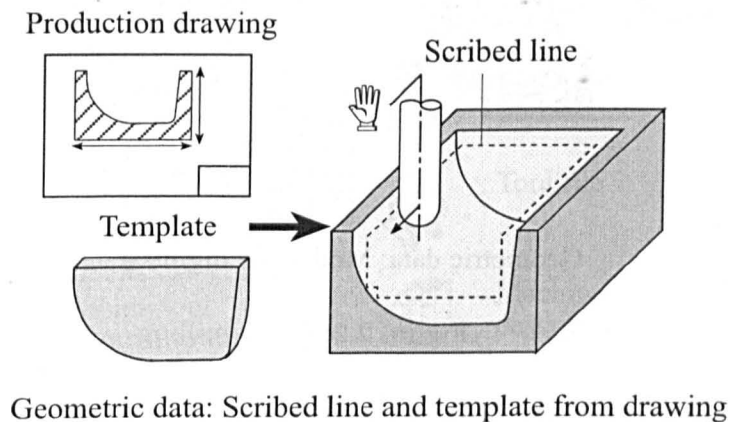
Figure 2.1: Manually controlled milling

Due to inferior and barely reproducible manufacturing accuracy, as well as the exacting demands on manual expertise, the extremely time-intensive production method of manually controlled milling has largely disappeared from use. Today it is employed only for preparing a part for rough-machining by coarsely removing material from large areas of the surface of a blank.

2.2.2 Copy milling and NC copy milling

Copy milling was a further development in machining methods for manufacturing parts. In this technique a tracer mechanically traces the profile of a model of the part to be produced line by line. The motion of the tracer is converted synchronously into a feed motion by means of hydraulic or electrical power-transmission systems. In contrast to manual milling, opportunities for optimising cutting conditions are very limited because the cutter is subject to the positive guidance exerted by the paraxial tracing direction of the machine. The production quality obtained is limited by the accuracy of the model as well as by the mechanical tracing operation and the transmission of the signals sent to the feed drives (Fig. 2.2).
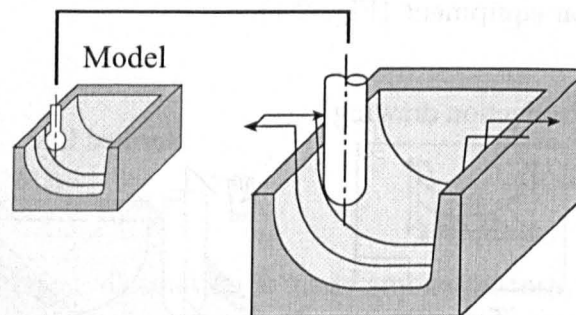
Geometric data: Model and digitised data

Figure 2.2: Copy milling

NC copy milling represented an advancement of the copy-milling process and an interim solution on the way to the introduction of NC technology. First the part geometry described in the pattern is digitised by line-by-line probing and the information thus obtained is then saved in the numeric control system in the form of milling paths. After supplementing process data such as spindle speed and feed rate, the resulting NC program can be used to mill the part. Decoupling the tracing operation from the machining process achieves considerably higher manufacturing and repeat accuracy compared to copy milling, with a simultaneous increase in flexibility. Thus depending on the performance scope of the CNC system, the process even permits a limited range of geometry manipulations such as mirror-imaging, rotation and offset of the finished NC data record. However, the technological limitations imposed by the milling direction and strategy being firmly prescribed by the tracing direction remain.

2.2.3   Manual NC milling

In manual NC programming, the user creates programs in a form that can be read directly by the machine control. The sequence of work steps is defined in records which have a standardised structure. Because the content of the individual words in a record is unique to a specific manufacturer, such an NC program can run only on a single machine type. Manual NC programs are written primarily for very simple geometries. One advantage of this programming technique is that no cost-intensive programming aids are required. Programs for parts with simple contours can be created quickly and easily. The usually qualified personnel can make necessary changes to the program directly by using the machine control's editor. Fig. 2.3 illustrates the individual steps required for manual NC programming.
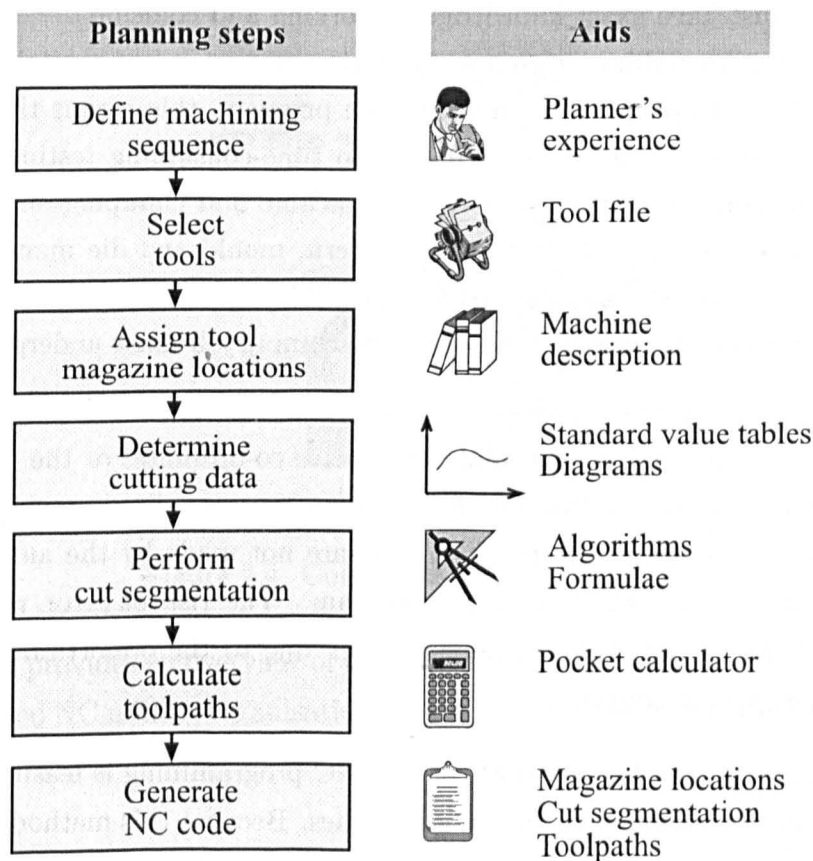
Figure 2.3: Fundamental procedure in manual NC programming

But manual NC programming has serious disadvantages, in particular when viewed

against the background of requirements in pattern, mould and die manufacturing. The parts range in pattern, mould and die manufacturing features numerous complex parts that are often characterised by free surfaces. NC programs for complex parts with free surfaces cannot be create manually. In this case, NC programming is only possible on the basis of CAD data using computerised NC programming systems. Conventional copy-milling machines, for which a model must be made, offer the only alternative for producing complex shapes.

A further drawback of manual NC programming is that programs must be written in a machine-specific format. The diverse parts spectrum in pattern, mould and die manufacturing requires that one each of a large variety of different machines must be available. A new program must be written to process a part on another machine.

The elaborate manual calculation of toolpaths is highly prone to error. The programmer must have exact knowledge of working and collision areas, especially when programming for milling machines. Graphics support is not available. In connection with the lack of options for simulating the program, this means that manually generated NC programs must be subjected to time-consuming testing on the machine to rule out collisions with the part, the machine and clamping devices. Due to the production of unique one-off parts in pattern, mould and die manufacturing , damage to the component must be avoided by all means. Therefore, when programs are generated manually, virtually every NC machining job must undergo a program test.

Manually generated NC programs are often unclear and hard to read. The various programming options, e.g. absolute or relative co-ordinates or the use of subroutines and machine-specific special functions support a personalised programming style. For this reason, changes in the program that are not made by the author require time-consuming familiarisation with the program. The risk of error when carrying out modifications to the program remains, e.g. due to the opportunity to use different co-ordinate specifications.

In summary, it may be said that manual NC programming is feasible only for a very limited part spectrum with simple geometries. Because this method of NC machining is not economical in pattern, mould and die manufacturing, it has become virtually obsolete and has been replaced by the application of CAD/CAM programming systems.

2.2.4   Computer-aided NC milling

Only the application of CAD/CAM systems opens up the direct way from design to manufacturing of the part. Here the NC program is created on the basis of a mathematical description of the part surfaces. The convincing advantages of this approach in manufacturing parts include higher accuracy and reproducibility, drastically reduced lead times, a marked increase in flexibility through the application of diverse milling strategies and the resulting higher stock-removal capacity manufacturing quality (Fig. 2.4).

In computer-aided NC milling, stand-alone data-processing systems are used individually or linked in a network, allowing for universality throughout the integrated process sequence.
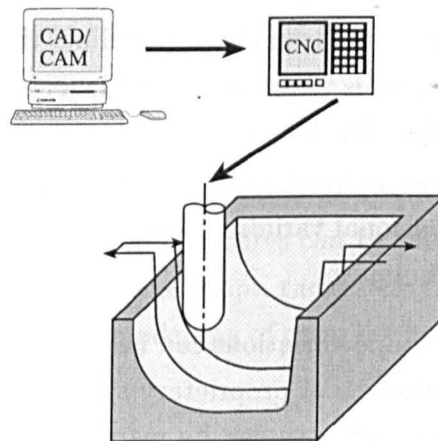
Geometric data: CAD description

Figure 2.4: Computer-aided NC milling

The following provides an overview of the most important technical design options of a computer-aided NC milling organisation for the pattern, mould and die manufacturing sector.

CAD systems

The major distinguishing features of CAD systems are the internal data structures for processing geometry. This type of representation is referred to as virtual rep-

resentation. Geometry can be displayed in the form of 2D or 3D models. In 2D representation, work is performed in a plane, comparable to the traditional method of working with a drawing board. Two-dimensional CAD systems are used to design parts developed from simple geometries, e.g. punching dies, cutting and welding tools. Complex geometries with free surfaces, like those commonly found in pattern, mould and die manufacturing , cannot be correctly reproduced in a 2D representation. Three-dimensional models are more suitable for these requirements. The B-REP (boundary representation) model provides a complete geometric description. The geometry of volumes, surfaces, edges and points as well as their mutual interrelationships are described in an internally generated virtual representation. Parts are frequently similar in structure, or can be classified in functional complexes, e.g. the column guides of cutting tools or forging dies. Through modification of only a few dimensions, this make it possible to adapt many one-off parts or assemblies to a new product geometry. A parameterized part structure is a practical aid that supports modelling of these parts. In parametric modelling, the modelling logic of a part upon which the design is based is saved and stored. Freely definable values are assigned to the individual entities. Explicit interrelationships can be defined among individual entities and dimensions by means of systems of equations or tables of measures. In this way, desired dimensional variations can be generated in a short time by applying parametric design techniques.

In parametric design, shape variations can be created in addition to dimensional variations. This requires the use of proprietary system macro languages with which the logical structure of the geometry can be mapped. In addition, non-geometric operations can be integrated into variant programs. One example is the design of forged parts, in which, based on the forging by way of calculation programs, technological requirements can be taken into account in shape design.

A further use of macro programming is the generation of command and drawing macros that are suitable for all areas of application in pattern, mould and die manufacturing. Standardised parts that are saved in parts libraries and can be used repeatedly in their stored form are examples of macros.

Linkage of individual applications, e.g. creation of geometry, generation of drawings and NC programming, provides significant support for the closed process sequence in the design and manufacturing of parts. Results obtained at different times and

mutually dependent are linked with each other. This means that changes made to one application will be carried out automatically in the other applications. For example, the production drawing depends on the 3D model. When the model is modified, the corresponding changes will be effected automatically in the 2D drawing if an associative link exists. Regeneration of the drawing is not required. If changes are made to the drawing, the 3D model and any submodels will be updated and related NC programs will be eliminated or recalculated, for example. This approach ensures consistency among the various submodels. This is an important system functionality for pattern, mould and die manufacturing because modifications induced by customers often appear later in the process sequence. Expenditures of time and cost can be kept to a minimum.

Modern CAD systems provide functions that allow a high degree of automation for in the task of generating drawings. Any desired views and sections can be defined, based on the 3D model. Hatching and even dimensions can be inserted automatically. This system functionality meets the requirements of pattern, mould and die manufacturing in an ideal manner because generation of drawings for complex parts is also supported.

In general, the functions described are integrated as upgrade options in commercially available CAD systems. The functional features can be put to use in accordance with the task at hand. In this respect, the scope ranges from CAD systems for simple geometries with 2D display to the modelling of complex parts with 3D CAD systems.

NC programming systems

The functional features of NC programming systems can be illustrated based on the general operational sequence of computer-aided NC programming (Fig. 2.5).

This permits complete computer-assisted programming of the machining tasks in pattern, mould and die manufacturing.

The description of the task is divided into two parts: geometry and technology. First, the geometry is defined, i.e. the description of original and final geometries. The geometric description is either designed directly in the affiliated CAD model-and is thus already available in the proper virtual representation-or imported by way of an interface. Loading CAD data into an NC programming system causes problems in

making the required data available.
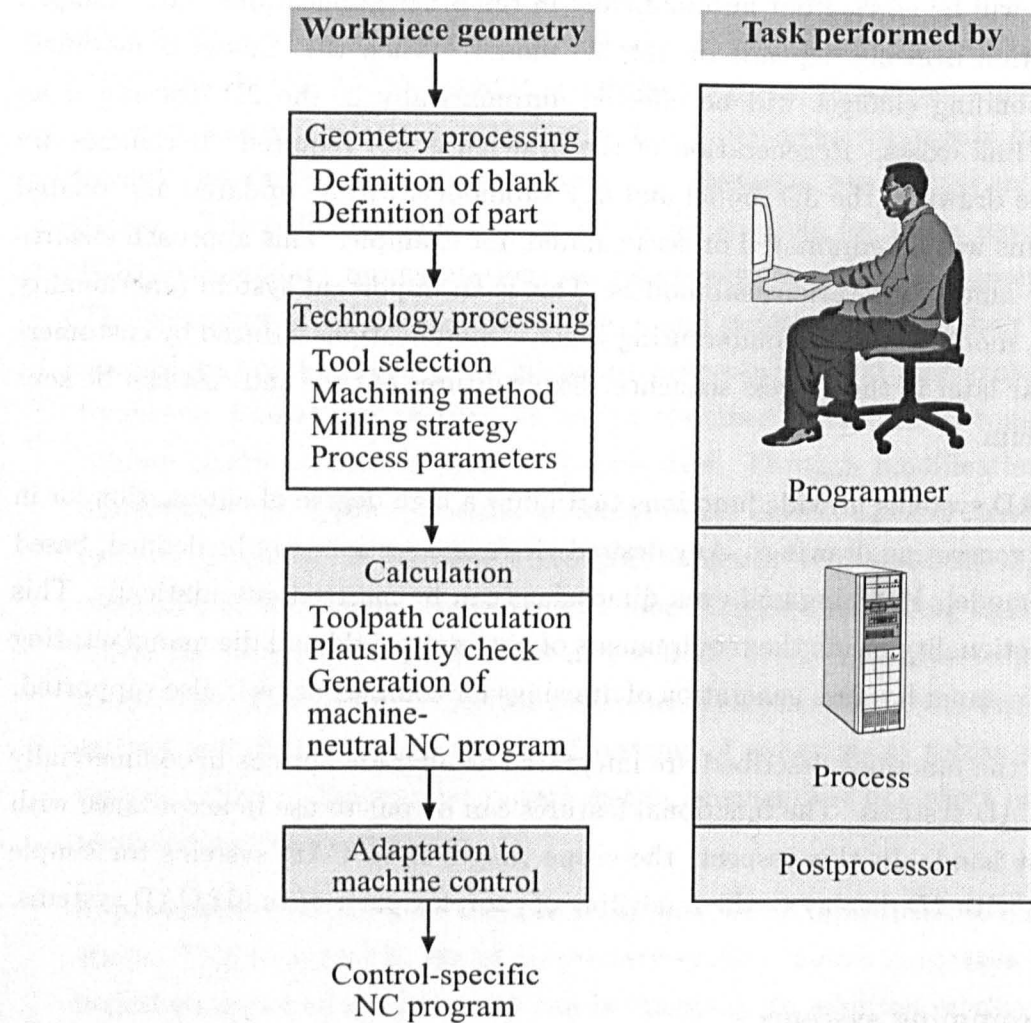
Figure 2.5: Computer-aided NC programming

The currently most commonly used interfaces VDA-FS surface interface (VDA = Association of the German Automobile Industry) and IGES (Initial Graphics Exchange Specification) can transfer geometric data from 2D and 3D models. The industry hoped to obtain improved data quality in interface transfers with the development of the STEP (Standard for the Exchange of Product Model Data) interface. This interface was supposed to make possible the exchange of product- and production-related data for the entire life cycle of a product. This is not yet possible with the current development level of the STEP interface. For this reason, the trend in data exchange between CAD/CAM systems is moving toward direct interfaces. The in-

ternal representation of the data of one system is converted directly into the display format of another system. This permits complete exchange of all data, but requires an interface between each pair of systems. In modern NC programming systems, geometric data can also be imported in the form of volume models, e.g. B-REP models from a CAD system. The advantage here is that no geometric data are lost and thus no time-consuming and error-prone re-designing is necessary. The geometric data in an NC programming system must be absolutely complete and met the required level of accuracy because they serve as the basis for all further NC calculations. Any incomplete or inaccurate information is incorporated directly into the calculated NC paths, which may result in defects in the finished product or even loss of the part. The starting geometry may thereby be the final form of the preceding process; it does not necessarily represent the crude state of the workpiece. Other geometries that must not be violated can also be specified in addition to the original and final geometries. These so-called protected elements may be, for example, tools for clamping the original geometry situated on the worktable of the milling machine. Naturally, these tools should not be damaged during the machining operation. Machining methods for the defined geometry are determined in the course of the subsequent technological processing.

Today's NC programming systems subdivide their functional features into several areas derived from practical application. As a rule, separate blocks of functions are provided for roughing, finishing and re-machining residual stock. Special milling strategies are made available for each individual block, e.g. axis-parallel or contour-parallel clearing cycles for cutter fields when roughing in layers. Besides these, there is an immense number of additional process parameters that have been integrated in NC programming systems for a fairly long time. Important performance characteristics of systems that are suitable for application in pattern, mould and die manufacturing, but are only partially supported by present commercially available systems, will be examined below.

Clamping devices can be filed in a catalogue and displayed when needed. The opportunity to define universally valid rules for clamping also makes it possible for the system to generate proposals for workpiece clamping. By specifying clamping devices, information about them can be included in the calculation and they can be incorporated into a collision check, for example.

The system can also support tool selection. Computer-oriented documentation of all relevant tool data is a prerequisite for automated tool selection. These tools are managed in the form of files so that they are available for on-screen access. NC programming systems offer convenient input and editing functions for mapping and building a tool library. Standardised libraries can also be imported by way of interfaces and converted into the system's internal display format.

Various system functions can be used to determine technological data. In particular, these include the selection of cutting materials, determination of cutting parameters and the division of cutting zones. Methods databases and process information which contain the specific data are integrated in the programming system for this purpose. Fig. 2.6 shows a sample structure of a CAD/CAM system database.

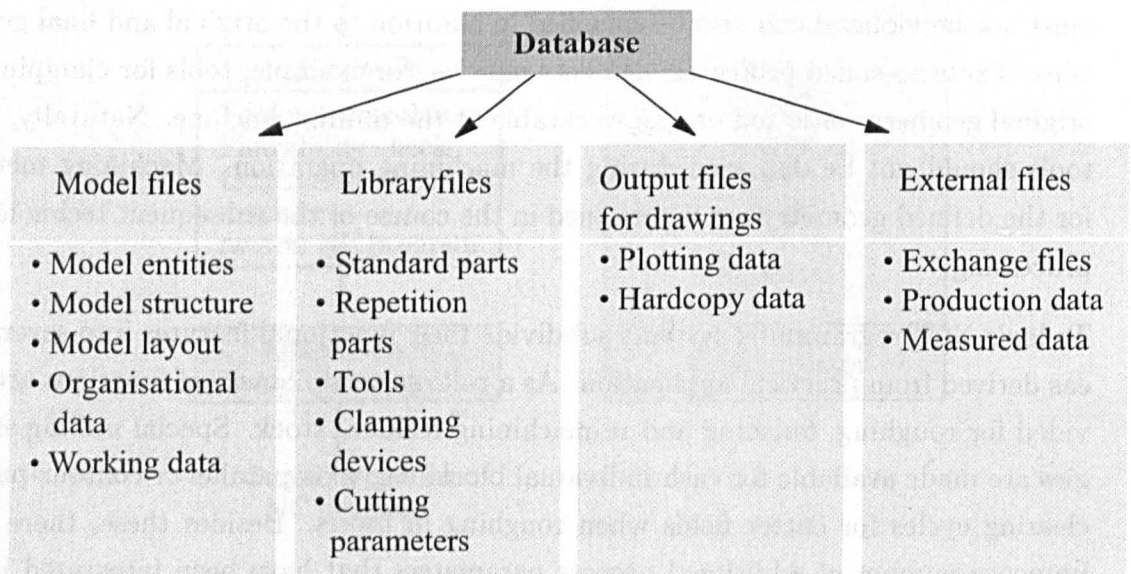| Database			
Model files	**Libraryfiles**	**Output files for drawings**	**External files**
• Model entities	• Standard parts	• Plotting data	• Exchange files
• Model structure	• Repetition parts	• Hardcopy data	• Production data
• Model layout	• Tools		• Measured data
• Organisational data	• Clamping devices		
• Working data	• Cutting parameters		

Figure 2.6: Database of a CAD/CAM system

The areas or cutting zones that will be traversed by the tool must be determined based on the geometric and process data and the selected milling strategy. This determination of cutting zones can be automated. For this purpose, systems provide functions for

- calculating cutter fields from a particular view

- detecting flat and steep areas

- calculating areas of residual stock

- taking depth and height limits into account

- taking protected elements into account

Particularly in the case of complex geometries with free surfaces, these functions are necessary to ensure efficient processing on the machine tool.

Toolpaths are calculated automatically, taking the contours of the part as well as any defined offsets and wall thicknesses into account. The parameters for the calculation are stored in the system and can be reused subsequently or at a later time for an identical or similar machining operation. To an certain extent, some systems also provide functional features for optimising toolpaths. The essential aim of optimising tool travel is time- and cost-effective production. Possible results include minimising the number of required tool changes by modifying the machining sequence or shortening traverse paths, for example.

The aim of introducing and utilising computer-assisted NC programming is to quickly generate error-free NC programs and relieve capital-intensive manufacturing facilities of preliminary preparatory tasks. For this purpose, modern NC programming systems provide functions for simulation and collision checks which may encompass the entire machine environment. These functions enable the user to image all the components involved in the machining operation, such as tools, clamping devices, workpiece and machine, and to check the manufacturing process in a simulated run on the computer. This, in turn, makes it possible to achieve one of the important goals of pattern, mould and die manufacturing, i.e. reliable and highly reproducible quality of the produced parts.

Similar to CAD systems, NC programming systems provide variant programs that support recurring tasks. In addition to geometric data, geometry macros include the toolpath commands required to machine the cutting zone. Defined sequences, e.g. for milling a groove, can be invoked together with the associated tools and cutting data by means of technology macros. In variant programmes, similar parts are combined into parts families, allowing the parts to be produced using the same parameterised machining program. Assignment of the parameters to be processed makes variant programming possible, so that recurring machining sequences can be

taken into account. However, due to the different geometries involved, this is only conditionally possible when generating free surfaces. The diverse geometries pose varying demands on the machining operation, making standardisation feasible only for simple geometries and milling operations, e.g. milling a plane surface.

In general, the processing of geometric and technological data in the processor of an NC programming system ends with the creation of a machine-independent NC programme. This generalised manufacturing program must then be converted into a control-specific NC program. The conversion is performed with the aid of post-processors that take particular machine properties such as kinematics, axis length, number of axes to be interpolated, tool and pallet changes, etc. into account. Further information can be derived in addition to the control programme, e.g. programme listings, set-up plans, tool lists and calculation of machining and idle times required for production.

CAD/CAM system concept

Various system concepts may be selected to implement the application of CAD/CAM in pattern, mould and die manufacturing (Fig. 2.7): linkage based on a common virtual representation of the model as an integrated solution, or the coupling of two separate systems by means of standardised interface or a direct interface.

In integrated CAD/CAM solutions the CAD and NC software access the same database. The virtual model of the part and blank geometry generated with the aid of the CAD system can be further processed directly in the NC module. There is no loss of information during the transfer of the virtual model from one system to another. CAD and NC data are linked associatively and are managed by one of the systems so that inconsistencies in the data organisation do not occur because part models are modified automatically. An identical user interface and the fact that the user need operate only one system are further advantages. The fact that integrated CAD/CAM solutions, depending on the machining task, do not provide the full CAM functionality required for pattern, mould and die manufacturing and thus not all NC machining jobs can be performed with a single CAD/CAM system is an apparent disadvantage. This makes the application of additional systems necessary and requires the linkage of stand-alone systems. The CAD system and each of the individual CAM systems has
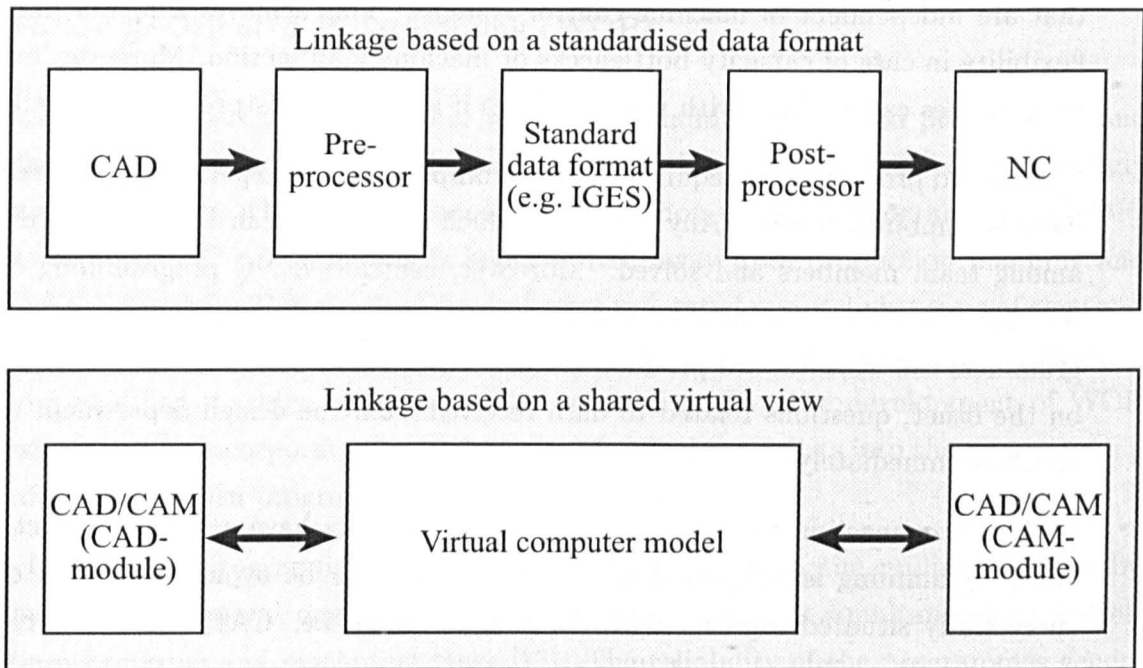
Figure 2.7: CAD/CAM system linkage

its own virtual representation of the part geometries. Because CAD and NC data are not coupled, more organisational effort is required to manage the CAD data and the NC part programmes than is necessary with integrated CAD/CAM systems. Because geometric data are exchanged by way of interfaces, it is often necessary to edit the geometry in the NC programming system. Since data are not transferred from the NC system to the CAD system, the corresponding NC programmes must be updated if the geometry is altered. Advantages are the available functional features that can be used to perform complex tasks.

CAD/CAM in job scheduling and planning

In an organisational classification of computer-assisted NC manufacturing with the aid of CAD/CAM systems a fundamental distinction is made between centralised and decentralised generation of NC programmes. Decentralised programming is always machine-oriented or machine-linked. In organisational terms, centralised NC programming is either a function of production planning or forms a separate department. An advantage of centralised programming is the ability to create milling programs

that are independent of machine control systems. This achieves a higher degree of flexibility in case of capacity bottlenecks or machine malfunction. Moreover, existing programmes can be used with new machines if a suitable postprocessor is available.

Centralised programming requires that the competence and experience of all programmers is combined locally. Any problems which may occur can be discussed directly among team members and solved. Moreover, centralised NC programming can be integrated locally with the design department. Due to this physical proximity, programmers can work toward production- and NC-oriented design on the one hand and, on the other, questions related to data received from the design department can be clarified immediately.

Lack of a connection to manufacturing operations may have a negative effect when NC programming is integrated in this way. This can be avoided if design can be successfully situated together with NC programming, i.e. CAD and CAM, close to manufacturing. The physical distance impairs communication with the workshop. Enquiries related to centrally generated programmes often require the presence of the programmer in the shop. This results in numerous disruptive impulses for centralised programming. As a product of centralised programming, the shop receives a machine-specific programme originating from the machine-neutral source programme following a postprocessor run. Due to the fact that the machine operator is not familiar with the procedure used to create programmes, modifications at the machine are problematic. Moreover, changes made at the machine affect only the machine-specific programme, but not the machine-neutral part programme.

In contrast to more shop-oriented copy milling, centralised computer-aided NC machining calls for an off-line process organisation: The course of the process is already determined to a large extent during creation of the NC programme. Aside from overrides for feed rate and spindle speed, the machine operator can no longer intervene to incorporate his or her practical know-how. In view of the demanding machining task involved in milling parts, this process-remote arrangement requires extensive knowledge of metal-cutting technology on the part of the programmer.

Workshop-Oriented Programming (WOP)

Based on this perception, together with the demand for increased productivity and effectiveness, the focus during the past few years has once again moved increasingly toward the shop, whereby the concept of Workshop-Oriented Programming (WOP) has evolved. NC programming is being shifted away from production planning and into the workshop. Programmes are no longer generated remotely in terms of time and space but, instead, close to the machine and directly by competent and increasingly more qualified machine operators. The essential goal in the development of WOP systems was to incorporate the competence of skilled specialists into the programming process and return programming it to the workshop.

A CAD/CAM programming system, coupled directly with the milling machine by way of a background queue management function, permits simultaneous execution of programming and machining tasks [17]. The reliability of the programmes generated by the NC programming systems is the technical prerequisite for this procedure. Tiresome and strenuous monitoring of machine operations, hand ever-ready at the emergency stop button to react to possible collisions, is no longer required. The time saved thereby can be utilised more productively to prepare the next milling program. By working with an actual instead of a setpoint situation, the machine operator can concentrate directly on the current workpiece and, for example, detect the actual casting oversize for rough machining, whereas the external NC programmer must base his work on standard situations [35]. In addition to a reduction of lead times, this combination of programme generation and milling returns responsibility to the know-how specialist in the workshop. The superior qualifications of specialists in the workshop are characteristic of pattern, mould and die manufacturing companies. This competence can also be put to use for programming by using WOP systems. Moreover, shifting programming to the workshop enhances the value of the jobs there and thus leads to increased employee motivation. Economic benefits result in two areas: On the one hand the specialist uses the time during which he would otherwise be monitoring the machine to create new programs. On the other, shifting programming tasks to the shop saves capacity for other tasks in production planning.

However, a disadvantage of the WOP concept is that NC tasks performed by the operator are distributed between two devices: the WOP workstation and the milling

machine control. Logically, this results in the demand for combining these two operating units into a single control and programming device. The actual situation, as it exists on the machine table, is reproduced virtually on the screen. This puts the operator in a position to define and follow all manual, standardised and complex traversing movements at any time in a graphic way. In addition to the part itself, the entire environment of the milling machine and clamping devices are depicted in a virtual image, permitting a comprehensive collision analysis. This represents an enormous gain in safety and reliability, particularly in rough machining operations. Because the flow of data to the machine is bi-directional, the operating unit not only sends instructions to the machine, but is also supplied at all times with information about diverse machine data such as axis positions, feed rates and spindle speeds as well as pending messages, as is the case with conventional stand-alone NC controls. This puts the operator in a position to monitor, control and trigger all processes on the machine. It allows for noticeably more efficient execution of procedures such as alignment and accurate detection of the blank, and thus leads to a correspondingly significant reduction in job-preparation and machine operating times.

2.3 Variations of the milling process

Milling is characterised by a rotating tool motion, a usually multi-edged cutter with an assigned cutting motion and a feed motion perpendicular or at an angle to the axis of rotation of the cutter. This results in the process variants shown in Fig. 2.8, which place stringent requirements on NC programming in accordance with the complexity of the workpiece geometries to be machined. The different variations and their specific NC-related features will be explained in more detail in the following.

In 2.5-axis milling, the cutter moves with its end face and/or periphery along any desired contour. The cutter moves simultaneously in two axial directions. This process is a variation of two-axis milling, whereby the third axis is controlled by a feed motion. 2.5-axis milling is the standard process used for rough-machining parts.

The aim in developing three-axis NC machining was to reduce the time required for mechanical processing. This milling process is characterised by the fact that although the position of the cutter tip is controlled in a continuous path, the direction of the
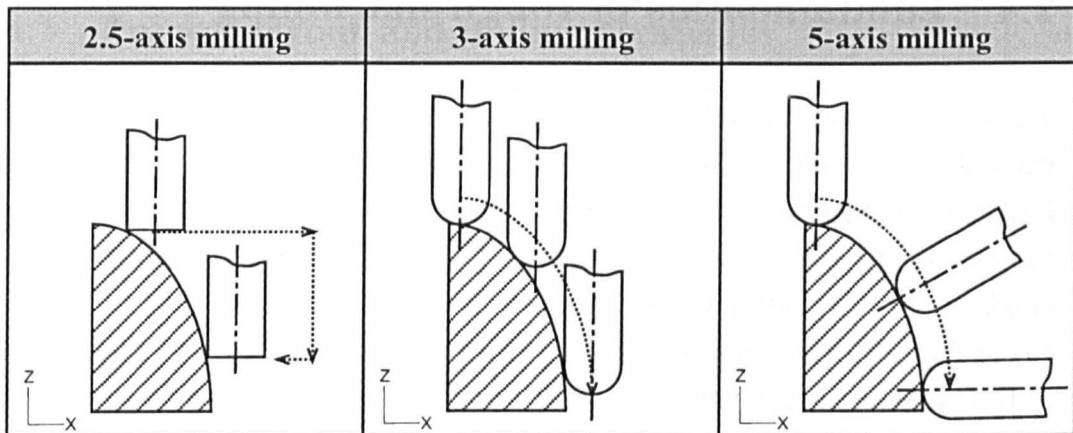
Figure 2.8: Variations of the milling process

cutter axis cannot be altered by the control. When the path is calculated, a permissible peak-to-valley height or surface roughness is maintained. This milling technique is used for finish-machining free surfaces.

In contrast to three-axis machining, a five-axis process provides an opportunity to tilt the tool relative to the surface of the part. This requires two rotational axes in addition to the three simultaneously controlled linear axes. In the case of curved surfaces, this technique achieves the same groove depth as three-axis milling, but with fewer milling paths and thus results in shorter machining times. Uniform contour adaptation by the cutter to the part produces a better surface finish, thereby decreasing the effort required for re-machining. Five-axis roughing places extreme demands on the control of the machine tool. The rotational axes must be capable of producing very high feed rates in order to ensure consistently high cutter feed. This is close to impossible, particularly in the case of HSC technology, which operates at very high feed rates. The share of five-axis milling in machining parts will continue to diminish more and more in the future as the use of HSC milling machines continues to spread. Machining on five-axis milling machines with two clamped axes (3+2) achieves a rationalisation effect by utilising the advantages of three- and five-axis milling while simultaneously compensating their drawbacks. Demands on the NC control and on the drives of the rotary axes are less severe. The direction of the cutter axis is adapted to the surface of the part area by area. So, although the uniform mesh conditions obtained with five-axis machining cannot be achieved, unfavourable cutter-part constellations can be avoided.

2.4 Fundamentals of rough machining

The aim of rough machining is to maintain a uniform residual offset on the part contour while achieving maximum rates of metal removal. This requires the use of large tools and a process layout in which the tool and the milling machine are pushed to the maximum permissible loading limits. Thus in the concept of rough machining the emphasis is on exploiting the performance limits of machine, tool and cutting materials to obtain the maximum rate of metal removal per unit of time [11]. During the course of HSC application, the objective of the roughing process has evolved from obtaining maximum stock-removal rates to achieving a sufficiently good and, above all, constant geometric adaptation to the part for semi-finishing and finishing. Ideally, the roughing operation should be immediately followed by finishing. As a result, the demand for increasing the rate of metal removal has recently become less important than the objective of saving on time-intensive semi-finishing operations. However, the costs being evaluated are those incurred for the manufacturing process of roughing. They must be lower compared with other manufacturing processes and thus are subject to the constant restraints of cost-reduction and optimisation. For this reason, the rate of metal removal must be harmonised, applying economic aspects, with cost factors such as tool wear, for example. But there are still basic prerequisites that are indispensable for a roughing process, since it would not otherwise be economical. The part must not be damaged or destroyed. This means that no movement of the milling machine may remove stock from the area of which the part is composed. The milling machine must not be destroyed. Traversing movements that result in damage to the machine, e.g. through collision of the machine head with the part, must not occur. The milling cutter must not be destroyed. No traversing movements may be executed that violate tool specifications, e.g. not plunge-capable. Material must always be removed completely from areas cleared by the roughing process. There should be no areas of residual stock that were not cleared due to inadequate rough-milling, or such areas must at least be evident for subsequent milling processes. All these requirements culminate in the fundamental demand for a guaranteed high level of process reliability. Therefore, the aim must be to apply methods in which process reliability is ensured and manufacturing costs are optimised.

2.4.1 Process layout and milling strategies

Implementation of the required economy and process reliability of the roughing process is rigorously bound to an adapted cut segmentation and/or milling strategy. In addition to the thermal load on the cutter, which essentially can be controlled by way of the cutting speed, mechanical load is contingent on contact parameters. Influencing variables are

- axial infeed a_p

- radial infeed a_e

- feed per tooth f_z

- the applied milling strategy

As shown in Fig. 2.9, the drilling capability of the tool used is a prerequisite for conventional copy milling, i.e. the surface-driven generation of a milling path. Consequently, it is not possible to use a torus mill. Moreover, the changing contact conditions associated with this strategy also result in an increased load on the tool tip.
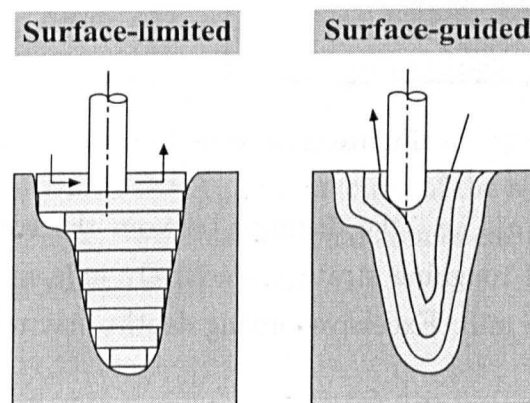
Figure 2.9: Alternative roughing strategies

In contrast, removing stock layer by layer with a peripheral cut produces more uniform contact conditions due to limited-area machining, whereby a higher cutting capacity and process reliability can be achieved. The limitation to tools with drilling capabilities also no longer applies because axial infeed to the next cutting plane can be

performed by means of a slightly inclined, linear or spiral infeed strategy. For this reason, parallel-stroke milling in layers is the standard strategy for roughing.

The blank and part geometries are machined on multiple z-profiled layers. The resulting contours represent the border between the material to be removed and that which will remain. The contour is actually laid bare by reciprocal milling paths or contour-adapted milling paths on the respective layer within the limiting contour (Fig. 2.10). Drawbacks of the reciprocating milling motion are changing contact conditions for climb and conventional milling and the interrupted metal-cutting process. For this reason, contour-adapted paths have become generally accepted as the standard strategy for clearing cutter fields in a layer.
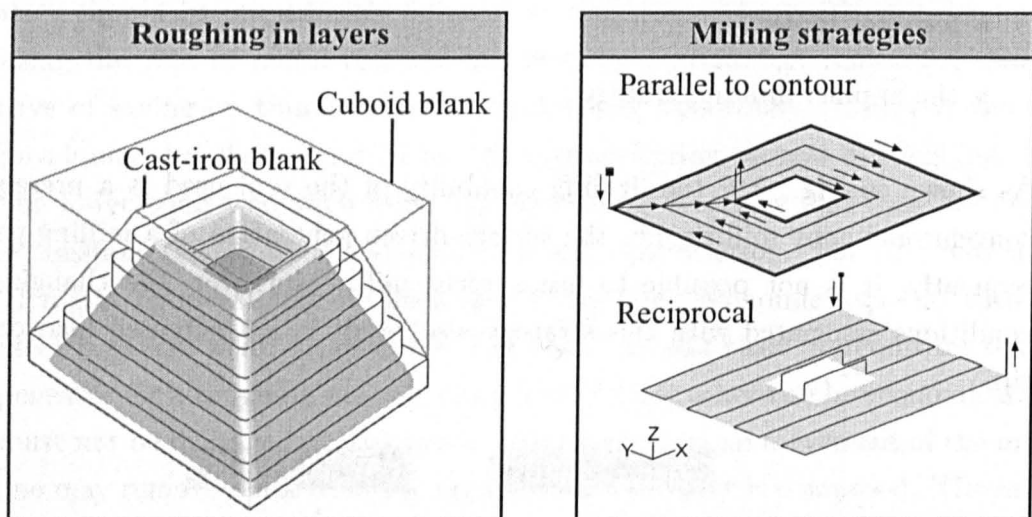
Figure 2.10: Roughing in layers

The depth of cut a_p, i.e. the distance between the consecutive cutting planes in the surface-limited roughing strategy, decisively influences the load exerted on the cutting edge of the mill. Excessive cutting depths may result in premature failure of the cutter.

Roughing is conventionally performed by milling with a minimum offset assigned to the part surfaces. This offset is then gradually decreased until a constant offset remains on the entire part contour. The problem which arises thereby is that only the minimum offset is known after each roughing operation and no information whatsoever about the quantity and progression of the maximum offset is available. Thus the actual

offset is not known. This may pose considerable potential risk for the remachining process. Information supplied by today's CAM systems is not sufficient for selective rough machining. A geometric description of the geometry of the blank following a roughing operation is necessary to determine the actual offset and its course along the surfaces of the part. Knowledge of the maximum offset and/or the current geometry of the blank is imperative for selective machining and for performing a cost-effective and reliable roughing operation.

2.4.2 Influencing factors

The efficiency of the roughing process is evaluated on the basis of the rate of metal removal as described above:

$$Q = a_p * a_e * f_z * z * n \tag{2.1}$$

This shows clearly that both the cutter diameter, which determines the obtainable radial contact variable a_e and the number of teeth z, and the infeed variables axial infeed a_p, feed per tooth f_z and spindle speed n should be maximised. However, the infeed variables directly affect the amount of the load exerted on the cutter and its cutting edges, which will be described in more detail below.

The type and magnitude of the load exerted on the tool can be illustrated with the aid of the cross-sectional area of cut A_{sp} as a function of the nominal pressure angle φ. Under the existing constraints, the cross-sectional area of cut results from the product of the axial depth of cut and feed per tooth.

$$A_{sp} = a_p * f_z \tag{2.2}$$

A characteristic comparable to that of a ball-end mill emerges for clearing horizontal planes (Fig. 2.11). The maximum cross-sectional area of cut remains constant at a pressure angle of 90°.

Due to the previously generated milling path and the circular cutting-edge geometry, the cutter enters the material softly in a climb milling operation and then experiences a progressive increase in load until the maximum offset is obtained. From this point the cross-sectional area of cut exhibits a sinusoidal characteristic until the cutter leaves the material at an angle φ of 180°. The location of the point of transition between the entrance area and the area in which the full depth of cut is reached as well as the rise in the cross-sectional area of cut exhibit a direct dependence on the axial depth of cut [34]. Whereas in the case of shallow depths of cut the curve remains continuous during chip removal, the cutter is subjected to an abrupt load at large cutting depths, which can have a negative impact on cutting performance and process dynamics.
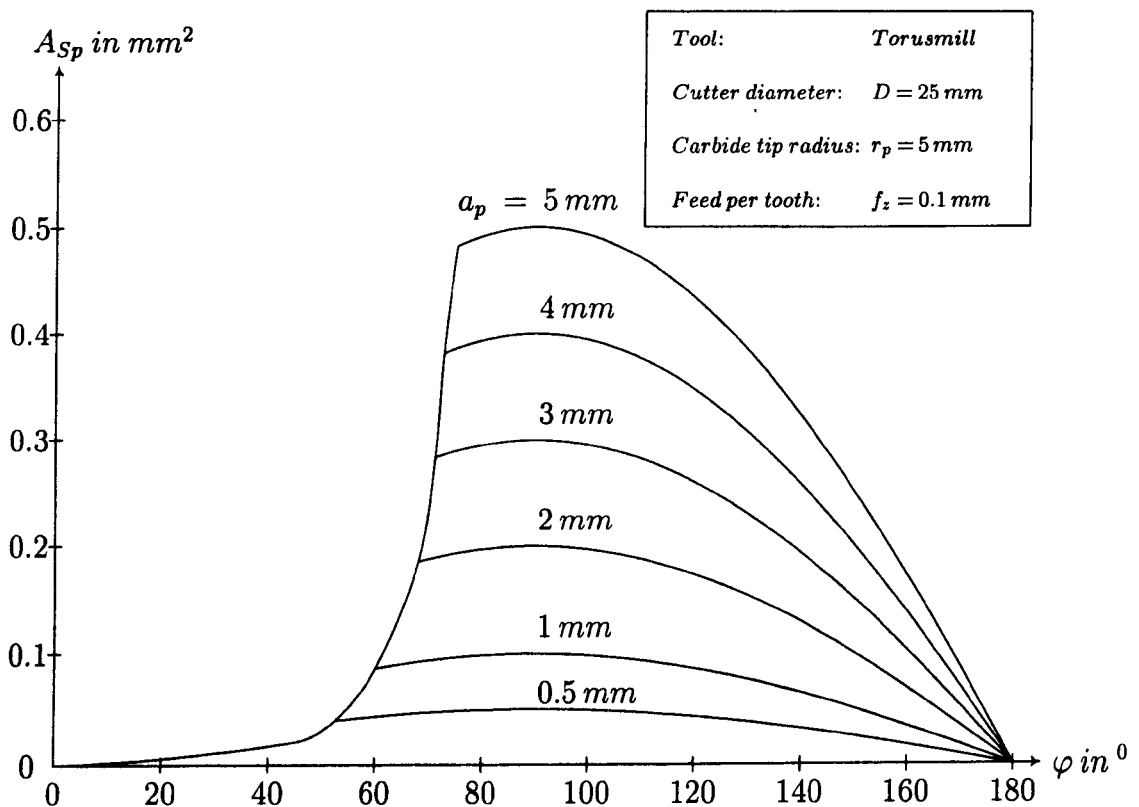
Figure 2.11: Influence of axial depth of cut on the cross-sectional area of cut

The feed per tooth also exerts a comparable influence on the cross-sectional area of cut (Fig. 2.12). Corresponding to the axial depth of cut, chip removal can be subdivided into the two areas in this case as well. However, it becomes clear that the pressure angle, at which the transition area is situated, does not change when feed is varied and

that the transition is of a markedly shallower form while the maximum cross-sectional area of cut remains the same [34].
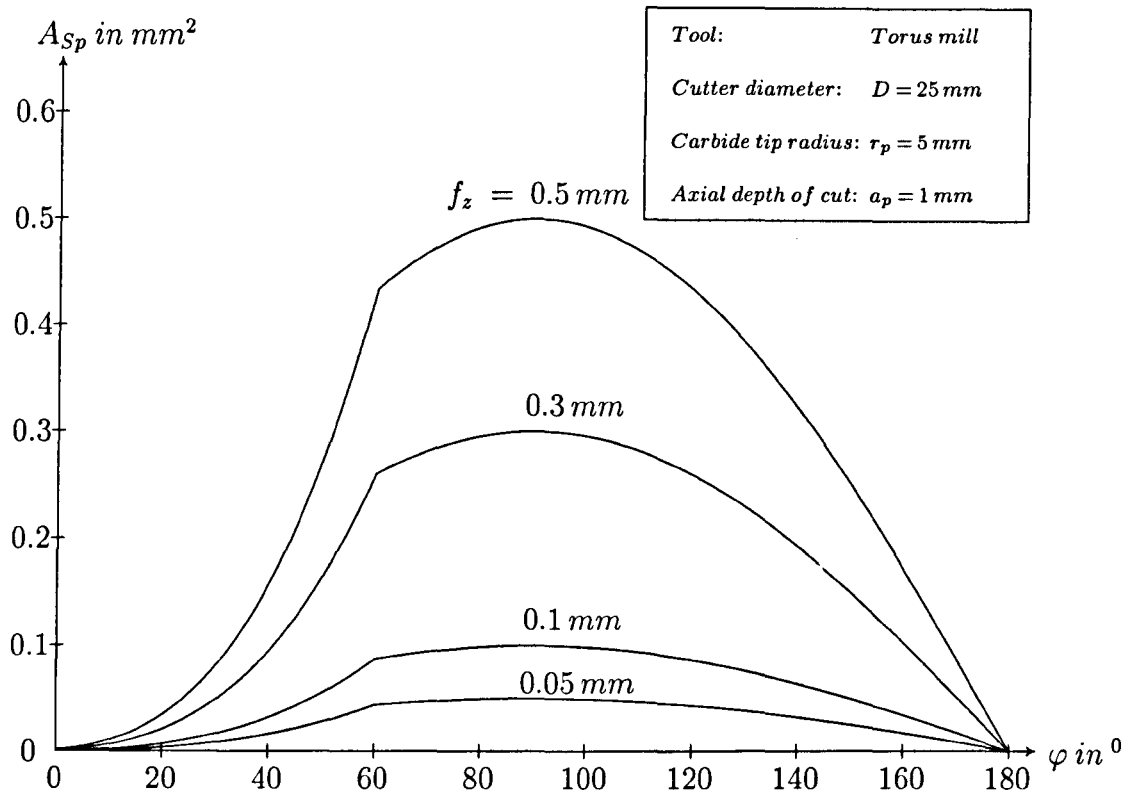
Figure 2.12: Influence of feed per tooth on the cross-sectional area of cut

Klocke [21] established this with the results of his investigation of the impact load on the tool's cutting edge. In doing so, he determined that, with increasing feed rate, the life of the cutter, i.e. the time of cutting until the cutter becomes worn, increases linearly until the load limit, dependent on the depth of cut, is reached (Fig. 2.13).

Whereas in the case of lower feeds per tooth the impact acts upon the cutting edge, the load shifts more to the face as the feed rate rises, lessening the tendency of the edge to break. Tool life travel diminishes markedly as the depth of cut increases. This effect may be attributed both to the increase in radial load as well as to the heavier impact load exerted on the cutting edge with increasing depth of cut.
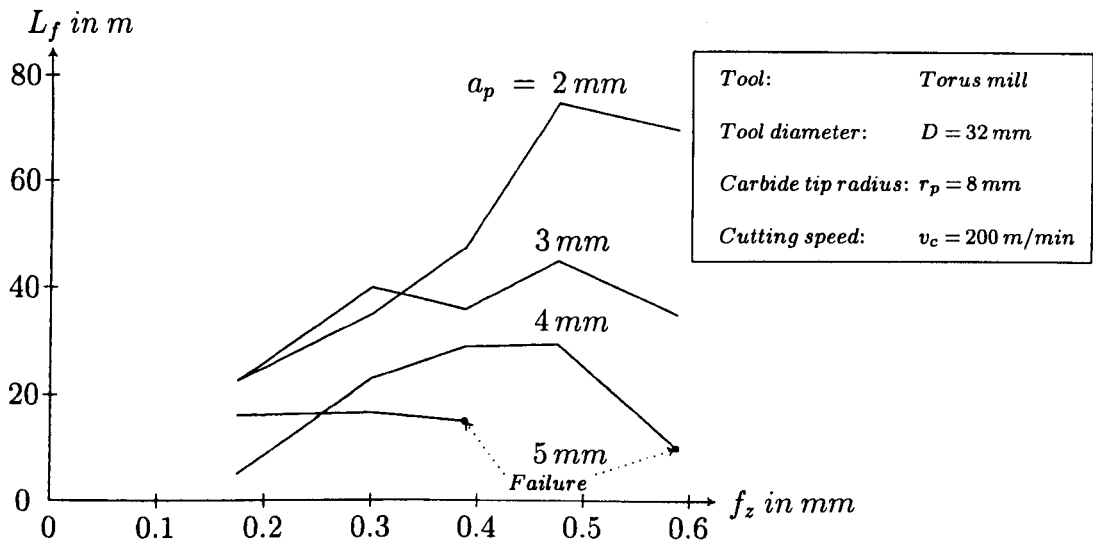
Figure 2.13: Layout of a roughing operation optimised for tool life

For these reasons, to avoid abrupt loads on the cutting edge, increasing the feed per tooth has a more favourable effect on the cutting process than increasing the depth of cut. In this connection, it should be noted that the evaluation variable for the roughing process, i.e. the rate of metal removal, in a combination of $f_z = 0.2mm$ and $a_p = 5mm$ equals that resulting from $f_z = 0.5mm$ and $a_p = 2mm$, whereby the latter permits a fourfold increase in tool life, as Zander [34] determined in trials.

In addition to the rate of metal removal, the maximum load on the machine is also taken into account in the layout of the roughing process. Particularly when viewed against the background of HSC, which virtually makes an investment in new and especially dynamic milling machines obligatory, existing machines are assigned a new role. Thus, today, it is the task of the older and less accurate machines to supply a sufficient number of pre-roughed parts for high-speed finish milling.

Although the available spindle speed and feed rate are usually adequate for efficient pre-machining, rigidity and stability often do not meet demands. However, this deficit can be countered by adapting the process layout. For example, the round carbide tips of the torus mill used for roughing parts can withstand heavy loads, they exert severe pressure forces on the spindle due to the disproportionately flat-spread chips. A reduction of the tip radius promises more efficient metal cutting and thus lower passive forces [21]. The number of carbide tips in contact with the material also has an impact on the magnitude of spindle/machine loading. Reducing the contact

width or the tooth feed may effectively decrease the forces, but it results in increased wear, as previously mentioned, because additional tooth engagement is required. For reasons of economy, therefore, the practice of simply reducing the number of carbide tips on the cutter symmetrically while maintaining the other parameters has become popular.

The selection of a suitable cutting material for the mill influences the economy of the roughing operation just as significantly as optimised process parameters and milling strategies. For the roughing process, the cutter material must be co-ordinated to the hardness of the material and load exerted by the process. Klocke [21] recommends the use of carbide as a cutting-tool material for machining steel. However, due to the diversity of materials used in pattern, mould and die manufacturing, this must be decided on a case-by-case basis and thus will not be dealt with in detail below.

2.4.3 Integration of process parameters and milling strategies into CAM systems

Cost-effective implementation of the demanding selection of tools and process parameters and of milling strategies described above in a safe, reliable and high-performance NC roughing programme depends above all else on the support furnished by the CAM system (Fig. 2.14).

Starting with the CAD geometry that describes the blank and the part, the systems perform an automatic or interactive distribution corresponding to the geometry-dependent strategies described above. Suitable tools and process parameters that ensure a technologically and economically feasible machining operation are assigned to these strategies. Milling strategies are then assigned to this linked system of blank and part geometries, cutter fields and tools. Finally, prior to calculation of the NC milling paths, feasibility is checked on the basis of the machine tool's performance capabilities.

While reading the advertisements and sales brochures for CAD/CAM systems that claim to be particularly suitable for pattern, mould and die manufacturing, the impression is quickly gained that the entire roughing process can be automated solely by utilising such a system.

CAD-surface description
Automatic or interactive
editing of CAD geometries
Allocation of offsets

Tool selection
Type
Diameter
Projecting length
Cutting-tool material

Milling strategiy
Clearing strategy
Infeed on contour
Downfeed

Process parameters
Cutting speed
Feed per tooth
Speed

Machine performance
Axis speed
Axis acceleration
Spindle speed
NC control

N0 X22.5Y30.5Z10.0
N1 X22.5Y30.5Z0.0
N2 X34.3Y12.6Z23.4
.....

Calculation functions
Geometrically oriented
NC data

Figure 2.14: Technology oriented CAD/CAM system

Despite the significant advancements in CAD/CAM systems during the past few years, virtually all systems exhibit deficits in terms of integrating technological aspects. Although the majority of these systems provide geometry-oriented NC functions, as a rule, they fail to take the technological requirements of the milling process into account. Thus the implementation of an optimal process technology essentially depends

on the level of knowledge and patience of the programmer. But these examples demonstrate that the manufacturing process of roughing continues to conceal an enormous potential.

Thus an optimum selection of tools, process parameters and, above all, the milling strategy would make it possible to increase performance many times over. Linkage of the variables necessary for a meaningful roughing operation can be realised through the development of new software technologies.

Chapter 3

HSC technology

Today, high-speed cutting (HSC) is certainly the most intensely discussed and most promising technological innovation in the area of metal-cutting manufacturing. Considerable sums are already being invested in this technology. The aim is to lower production costs while maintaining or improving quality. Until now, the benefits of this technique have been exploited solely for finish-machining parts. However, if the fundamental properties and requirements of high-speed cutting are applied to the roughing process, a great potential for optimisation can be achieved in that area as well. But this requires an understanding of this relatively recent technology.

3.1   HSC as a process

HSC is not as new as one might think. As early as the 1920s, the German C. Salomon investigated the effects of extremely high cutting speeds. In trials with circular-saw blades he attained speeds of up to 16,500 rpm and came to the conclusion that the cutting temperature reached a maximum and then fell to below the value critical for the cutting-tool material when the cutting speed was increased further. Meanwhile, it is common knowledge that this theory is not correct: the temperature rises with increasing cutting speed, accompanied by a corresponding increase in tool wears [20]. During the course of the decades, other scientists have also occupied themselves with this topic. Kusnetzov (1947), Kronenberg (1958) and Arndt (1972) all carried out ballistic trials in which the part was propelled past the tool. Kronenberg put forward

the theory that the cutting force first increased, but then sharply decreased. Arndt established that tool wear increased considerably at ultra-high speeds. It was not until 1979 that the Institute for Production Engineering and Cutting Machine Tools (PTW) at the Technical University of Darmstadt, Germany advanced into the high-speed range (47,000 rpm) in milling, using a magnetic-bearing-supported spindle developed in France. For the first time, the enormous benefits for industrial application became evident: machining time could be reduced by 50% with and improvement in both quality and precision. Subsequently, the fundamentals for industrial utilisation of this technology were compiled during a large-scale research project at the PTW under the supervision of Prof. H. Schulz [20].

3.2 Technological fundamentals

Compared to conventional milling, the HSC process is mainly characterised by a change in chip formation and chip removal. Because chip formation depends to a large extent on workpiece material, a corresponding description must be differentiated according to material properties. The process is elucidated below, using materials that tend to form continuous chips as an example. This group of materials includes most steels as well as aluminium and copper alloys. When viewed from a metallographic perspective, these materials permit deformation through displacement in glide planes [14]. This results in the steady production of chips in the shear zone and therefore to the formation of continuous chips. Three processes that must be considered in separate contexts occur simultaneously at the tip of the cutting edge:

- Plastic deformation and subsequent shearing of the material in the shear plane

- Friction processes due to relative movement between the continuous chip and the tool face

- Friction processes due to relative movement between the generated part surface and the tool flank

Deformation and shear

The material exhibits a resistance to plastic deformation, which is heavily dependent on the material itself as well as on temperature and the deformation ratio. Resistance to deformation decreases as the temperature rises, but increases with an increase in the deformation ratio. Thus, overall, resistance to deformation increases at high cutting speeds.

Friction on the tool face

Coulomb' s law describes the friction acting between two elements moving relative to one another in the stationary state:

$$F_{fric} = \mu * |F_n| \qquad (3.1)$$

where μ describes the coefficient of friction F_n and the normal force acting on the contact.

The coefficient of friction μ is thereby assumed to be a constant quantity. For high-speed cutting, this assumption is not tenable, because the coefficient of friction does not remain constant, but decreases as the cutting speed increases. Under extreme conditions, a fluid layer may form on the underside of the chip, i.e. the melting point of the workpiece material is reached. This reduces friction on the tool face, causing a decrease in chip compression and an increase in chip curvature [30]. The phenomenon of thermoplastic instability occurring thereby is the basis for processes in high-speed cutting. The reduction of chip compression results in an increase of the shear angle and thus to a reduction of deformation work [14].

Heating of the part is mainly a result of processes taking place in the shear and deformation zones. The portion of heating caused by tool flank friction, which increases as the cutting speed rises, amounts to less than five percent [14]. Altogether, less heat is generated per surface unit by HSC technology due to the smoother flow of chips. Consequently, the part is subjected to less heating than is the case in conventional machining.

Friction on the tool flank

Flank wear is also the dominant tool wear phenomenon in high-speed cutting. It is primarily conditional on cutting speed and infeed setting. The dependence of wear on cutting speed applies as much to HSC as it does to conventional machining. Tool life travel diminishes as cutting speed increases [14].

3.3   Technological effects

The massive increase in cutting speed causes a sharp rise in the temperature of the cutting-edge zone, which results in a decrease in the coefficients of friction between the cutter and the part. This reduces both tool-face friction and chip compression, whereby a change occurs in chip formation and the flow of chips.

The change in chip formation and chip flow causes a reduction in cutting forces, which, in turn, has a positive effect in terms of increased dimensional accuracy and improved surface finish. It also makes it possible to machine thin-walled parts and reduces the mechanical load on the cutter. Moreover, heat generated during the machining operation is mainly dissipated along with the chips, whereby the part is subjected to less heating and thus dimensional accuracy is improved.

The cutter is subjected to severe thermal stresses, which is directly reflected in increased wear. For this reason, HSC cutters must be meet special requirements with respect to temperature stability.

The actual primary aim of rough machining, i.e. a substantial increase in the rate of metal removal, is attained along with this acceleration of the cutting speed and the associated increase in the rate of feed. In addition, due to the high spindle speed, the cutter is subjected to less excitation of vibrations, which permits uncritical machining of vibration-sensitive parts.

Because resistance to deformation increases along with a progression in cutting speed, particularly in the case of high-strength materials like those frequently used in tool, die and mould manufacturing, the mechanical load on the cutting edge can be lessened by reducing the infeed setting and feed per tooth. As the rate of feed rises, tool life

travel first increases and, upon exceeding a distinct maximum value, decreases again. The initial increase in tool life travel can be attributed to the lower number of cuts made by the tool. These fewer separations of material produce less loading of the tool face rubbing against the part. With higher rates of feed, the cutting force increases, the path of the cutting-edge into the work is longer and the contact-zone temperature on the tool face rises. Thus the optimum feed rate depends to a large extent on the cutting speed.

In high-speed cutting, axial infeed has a relatively minor effect on tool wear characteristics. Similar results obtained from trials with conventional cutting speeds are also familiar [31]. Increasing the axial infeed setting a_p by a factor of 10 (from 1.5 to 15 mm) merely reduces tool life travel by approximately 20-25 percent (Fig. 3.1) [31].
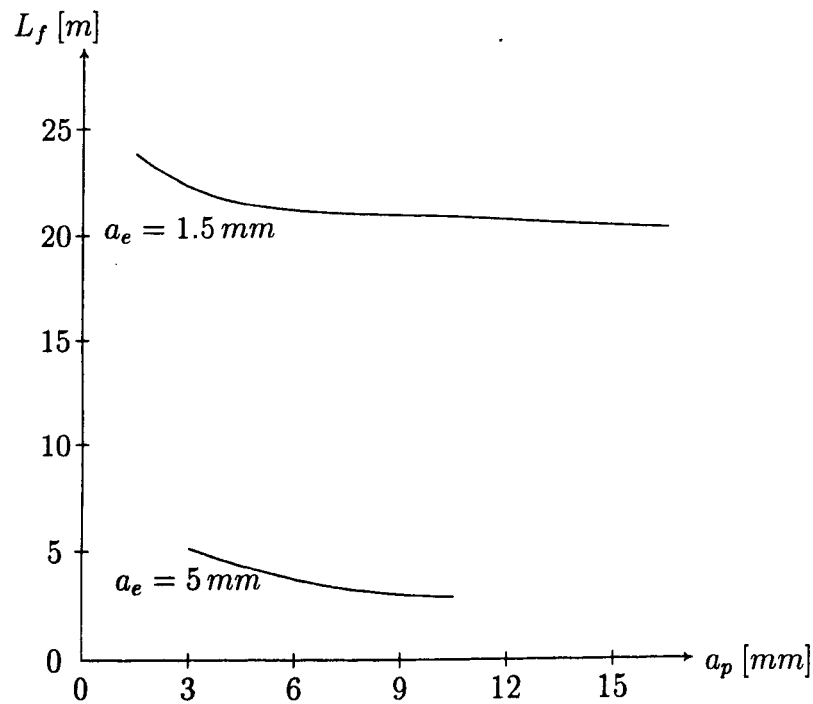
Figure 3.1: Influence of the width of cut on tool life travel

For this reason, the selected axial infeed setting should be as large as tool and part permit. However, the disadvantage of using a large axial infeed setting for roughing is poor contour approach to the part, which makes subsequent machining necessary. Thus economic criteria, e.g. duration of milling, the number of steps required for re-

machining, etc. should always be taken into consideration when selecting axial infeed adjustment.

In contrast, the radial infeed setting a_e has a considerable effect on tool wear. Tool life travel decreases as tool engagement increases. At the same time, there is a correlation between the radial infeed setting and the feed rate. In the case of low radial infeeds, a high feed rate must be selected so that the chip can be produced without severe pressure when the tool bites into the material. Because high stock-removal capacities must be obtained for roughing, a great deal of work contact is encountered there. This requires a reduction of the feed rate because, otherwise, the deformation work to be performed on the tool face would be too difficult (Fig. 3.2) [31].
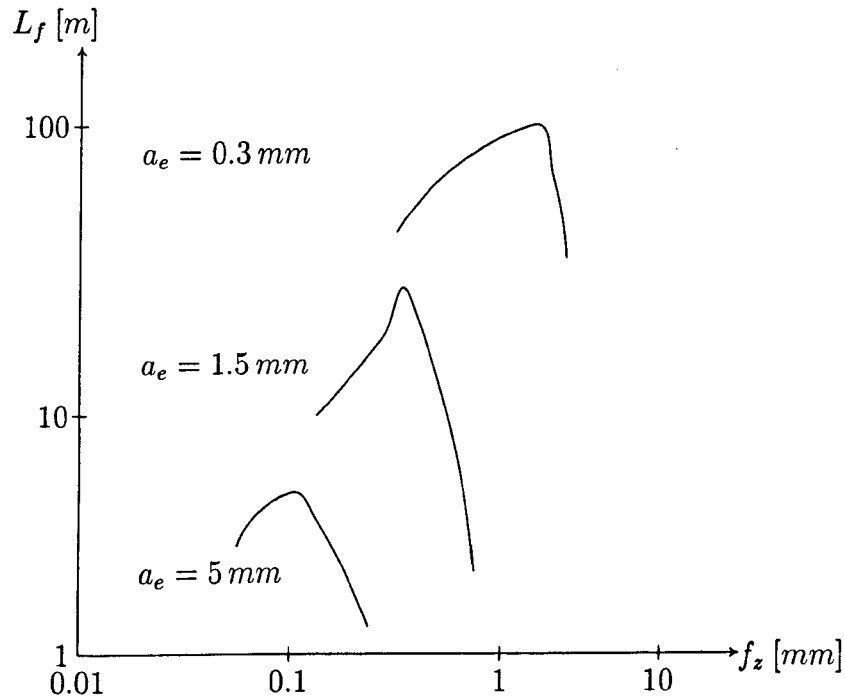
Figure 3.2: Tool life travel as a function of feedrate with different radial infeed settings

Due to the high temperatures encountered in HSC with large radial infeed settings, the elevated temperature hardness of the cutting tool material is exceeded and the cutter ultimately fails; the tool's cutting edge remains in contact with the work for a longer time as radial infeed increases and is thus subjected to more severe thermal

stress. At lower radial infeed settings, the non-cutting time of the cutter is long compared to the actual cutting time so that a brief period of heating is countered by a long cooling-down phase. On the whole, the radial infeed setting should be kept as low as possible. A working contact of approx. 5-10 percent of the cutter diameter is to be recommended. For HSC finishing, this radial infeed setting delivers the desired advantages of HSC, e.g. dimensional accuracy and a superior surface finish. But the economy of rough machining is mainly determined by the stock-removal capacity. For this reason, very large radial contact widths that exceed the cutter radius are selected for roughing. Therefore, the rate of feed must be reduced for rough machining.

The crucial aspect of HSC finishing lies in the altered chip formation and chip flow. The effects of the change in chip formation do not yet become evident simply by specifying a large radial infeed for roughing and the associated limited feed rates. Nevertheless, by taking appropriate measures, all the other benefits of high-speed cutting can be applied to rough machining, resulting in an enormous potential for optimisation.

3.4 Technological requirements

As the information above demonstrates, high-speed machining differs essentially from conventional milling. Accordingly, special demands are also made on its environment. These requirements must be satisfied to the largest extent possible in order to draw any economic benefits from the technology and exploit their advantages for roughing.

In addition to high feed rates, the axis-control drives must be capable of producing extreme acceleration and deceleration values without impairing toolpath accuracy. Therefore, although the masses being moved must be as small as possible, they must also exhibit extraordinary rigidity due to the strong forces generated during the roughing operation. The latter applies to the entire design of the machine, which must also exhibit excellent vibration-damping properties.

High cutting speeds require high spindle speeds and thus also high feed rates because the feed per tooth is only minimally influenced. Several requirements can be derived from this. The spindle must not only be capable of reaching high RPMs, it must also have a wide, infinitely variable speed range with adequate torque. Moreover, it must

be equipped with special bearings for maximum rotational speeds.

Research and development projects have demonstrated that vibration-free contact at the cutting edge is an absolute prerequisite for milling at high spindle speeds. The widely used tool-holder systems equipped with a quick-release taper mount per ISO standard are not suitable for high speeds because the machine spindle expands due to centrifugal forces, causing the cutter to lose stability and concentricity. Of several alternatives for an HSC-compatible interface between machine spindle and tool holder, the HSK mount, a short-taper shank with a flat seating, has gained acceptance. The HSK mount is preloaded and fixed in the spindle by means of the short taper and drawn against the flat seat by means of an internal-action chuck jaw. In this arrangement, the centrifugal forces generated during operation augment the clamping force.

The high quality of the HSC interface between machine and tool holder calls for an interface of equivalent quality between the tool holder and the high-performance cutter. In addition to standardised tool mounts, HSC-compatible hydro-expansion chucks and shrink-fit chucks have proved particularly suitable for clamping tools. Both ensure absolute freedom from unbalance and minimal concentricity deviations. In hydro-expansion chucks, a pneumatic medium surrounds a thin-walled expanding spring collet, by means of which hydrostatic pressure is exerted on the cylindrical shank, which in turn permits development of a fitting-joint pressure. The advantages of the expansion chuck are high transmittable torques and easy handling. Limited diametral flexibility and high acquisition costs are disadvantages. The action of the shrink-fit chuck is based on the thermal shrinkage fit, a long-successful principle of power transmission in mechanical engineering that is utilised for tool clamping applications. The front portion of the one-piece chuck is designed in the form of cylinder having a concentric bore with undersize. To connect the tool, the base is heated until the seating bore expands by the amount of the undersize and the required joining clearance and the cold tool can be inserted. After cooling down, a concentric tool seat is ensured. To release and eject the tool, the chuck is heated with the tool clamped, whereby the chuck body and tool must exhibit different thermal-expansion characteristics. Chuck bodies made of casehardened steel combined with carbide-metal tools are ideal for this arrangement.

Tools used for HSC must also satisfy special criteria. The prominent requirement on

HSC tools for roughing is adequate resistance to wear for applications at high cutting speeds combined with high stock-removal capacities. In concrete terms, this means temperature stability and hardness. Particularly when machining in steel, these tool properties determine the economy of HSC-oriented roughing. Deviations in rotational accuracy must be maintained at particularly low level to ensure uniform loading of all cutting edges.

The CNC system is the interface between the CAD/CAM system and the machine. The essential requirements placed on the control by HSC-oriented rough machining result from the complex, three-dimensional surfaces of the parts to be machined, which must be approximated during the rough-milling operation at high cutting speeds and toolpath feed rates while maintaining dimensional accuracy and process reliability. The still commonly used technique of interpolating cutter paths by means of linear path commands requires large quantities of data for the applied milling strategies, e.g. contour-parallel machining. The milling paths, described by mathematical models while maintaining a chord tolerance, are approximated by the CAM system in the form of linear path commands. This result is different path lengths between two NC positions and, where necessary, sharp changes of direction. Even though the chord tolerance applied for roughing is normally very coarse, the generated NC programs may easily be 10 MB and more in size. Thus it must be possible to transfer these extensive programs quickly from the CAM system to the control, where they can be either processed immediately or reliably stored. Increasingly, more advanced controls can interpolate the spline mathematics used for surface description in CAD/CAM systems. For the first time, spline interpolation in the control permits universal application of the mathematics used in the CAD system. The spline record generated by the CAM system for the description of cutter paths can replace several linear path commands. The decisive advantage of spline interpolation is said to be in the reduction in the number of NC records to be generated as well as in the smooth and continuous transitions between consecutive spline records. However, this claim has not yet been substantiated by practical application and thus the spline technique has not gained wide acceptance. High toolpath feed rates accompanied by high contouring accuracy is another demand on CNC systems and on the overall technology of the axis-positioning drives. Fig. 3.3 illustrates the principle of a HSC CNC system.

Ethernet Protokoll TCP/IP
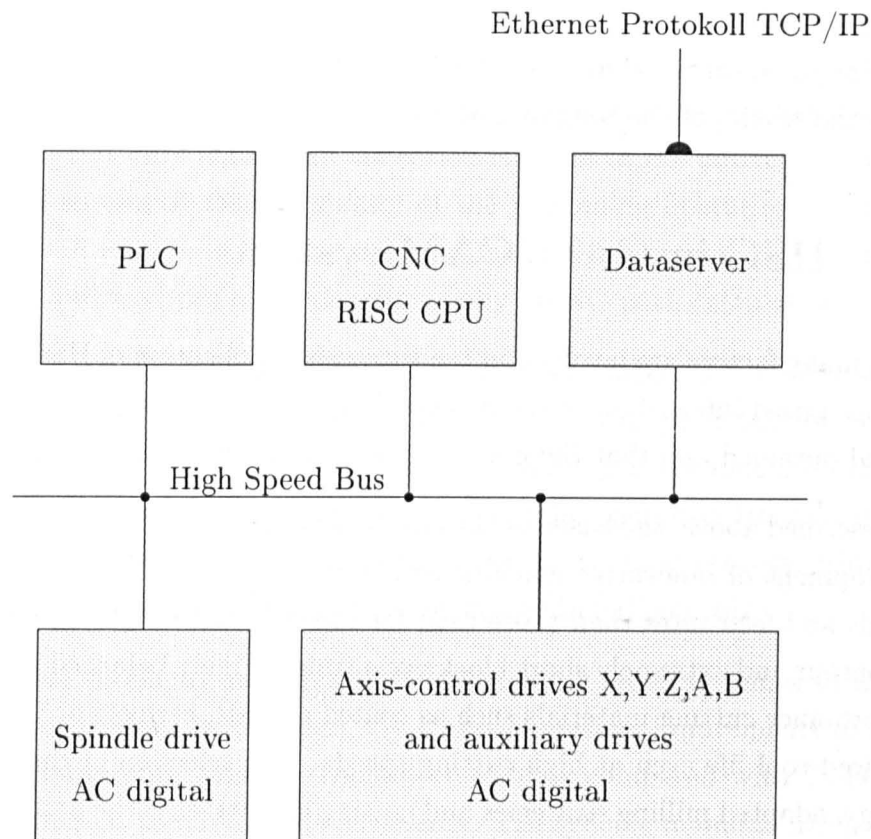
Figure 3.3: Schematic layout of an HSC CNC system

All components are connected by way of a fast internal bus. The drive units are of a digitally controlled AC design. The programmable logic controller (PLC) organises interaction between the control and the machine tool. In addition to diverse control tasks, the PLC also handles certain areas of process supervision. Supervision of the process is necessary to protect the machine tool, the cutter and the part, especially when quenched and tempered or hardened materials are rough-machined in an automatic sequence. During the roughing operation, a profile of the power input of the main drive emerges. This profile is permanently monitored with a safety allowance of 20 percent, for example. If power input increases due to cutting-edge wear or tool breakage, the feed is interrupted and the spindle is time-delayed and shut down. Depending on size and type, machines suitable for HSC-oriented roughing exhibit different static, dynamic and temperature-related errors. With modern CNC systems, these errors can be compensated by setting appropriate parameters. However, this is

possible only if the errors are a constant quantity of the respective machine model. Errors with wide variances cannot be effectively compensated. Fortunately, the tolerances required for roughing are relatively coarse so that such errors do not negatively affect the results of the roughing operation.

3.5 HSC in CAD/CAM systems

Thus many factors are involved in the successful application of HSC technology. Only the optimised interaction of all of these factors ensures that the expected results are indeed obtained and that the considerable investment pays off.

As described above, the basis for the practical application of high-speed roughing is the development of innovative machine and control concepts that permit higher spindle speeds and feed rates than those used for conventional roughing, maximum trueness to contour and extremely short block cycle times. Finely balanced tools made of high-performance cutting materials such as coated carbide, cermets or CBN guarantee the required tool life even at high cutting speeds. The selection of the appropriate technology, adapted milling strategies and cutting conditions is the additional prerequisite for HSC roughing.

In this interaction, the CAD/CAM system performs the important task of developing NC programmes based on the CAD data that are suitable for HSC application.

Diverse CAD systems have been developed on the basis of the different types of models, e.g. CSG (Constructive Solid Geometry), B-Rep (Boundary Representation) and free-surface models. Most CAD manufacturers include an NC programming module in their software package. The significant advantage here is that the system's internal geometry descriptions can be used as a reference for NC programming and the user is able to make specifically NC-related modifications and expansions to the CAD model. On the other hand, a few NC programming systems have succeeded in establishing themselves in the market as standalone software products and must be viewed as specialists in the area of NC path calculation. These systems convert existing geometric descriptions into their own internal data structures via standard interfaces such as IGES or direct interfaces to CAD systems. This is also one of the problem areas faced by such systems: the existing interface definitions are, in part, not restrictive enough

to define an unambiguous standard mapping specification.

A common feature of all commercially available systems is that NC path calculation and thus the control instructions use the geometric representation of the part as their sole reference. But only inadequate attention is given to the cutting-process parameters that are so crucial for the quality of the machining operation. This becomes evident above all when free surfaces are machined, where process parameters such as cutting speed and feed per tooth depend wholly on NC path calculation.

As previously stated in Chapter 2, the lack of process transparency and the segregation of planning and execution are considered to be a further disadvantage of conventional NC programming. In other words, the specialist working at the machine currently has no other choice but to have the machine perform the operation from start to finish. There is virtually no opportunity to intervene in the running process, aside from the override and spindle speed potentiometer on conventional controls.

Of course, these problems are intensified considerably when it comes to a multiple-axis finishing operation. In this case, the three-dimensional movements of the cutter lead to essentially more complex contact conditions compared with 2.5D roughing and thus to different technological constraints. The specific manufacturing situations associated with high-speed machining further complicate these conditions. These include a considerably higher feed rate as well as the new cutting-tool materials that, due to their extremely brittle properties, have a considerable effect on the roughing strategy.

A closed description of the free surfaces is required for roughing geometrically complex parts. There are a multitude of surface modellers available that permit an appropriate surface description. Thus the surfaces serve as a reference for describing the part. When one considers the machining step of roughing, which is usually necessary for machining parts in die, mould and pattern manufacturing, it becomes clearly obvious that the surface description as a geometric constraint for calculating tool travel is not sufficient for this machining step. In many cases, one must resort to an existing free-surface construction or a volume model for describing the blank. For this reason, two geometric descriptions, one for the part and one for the blank, are required for the roughing process. As early as the pre-finishing operation, only the surface description of the part is available as a reference model. Thus the problem faced by the NC

programmer consists in selecting tools, infeed settings and process parameters for a meaningful pre-finishing operation without having exact knowledge of the roughed part geometry (Fig. 3.4).
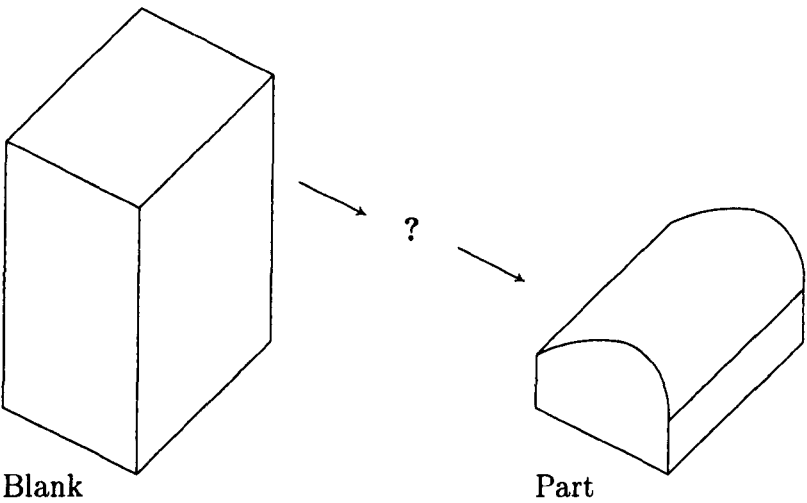
Figure 3.4: Problem confronting the NC programmer

Therefore, in practical applications, a constant offset is approximated by way of so-called offset surfaces that are situated at a given perpendicular distance from the part surface (Fig. 3.5).
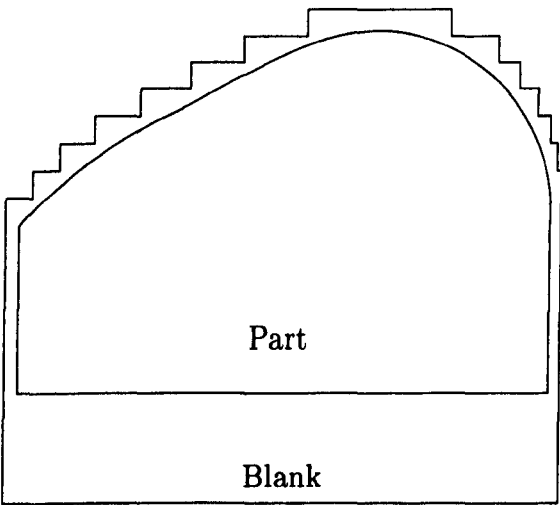
Figure 3.5: Geometric conditions prior to pre-finishing

Commonly available CAM systems provide a few mathematically derived milling strategies, e.g. reciprocal or parallel to contour. Unfortunately, little importance has been placed in the past on the technological constraints occurring thereby. Whereas, until now, the available machine tools, spindles and cutting tools have been sturdy enough to compensate for technologically adverse contact conditions, the goal of HSC-oriented roughing requires dispensing with such over-dimensioned reserves.

Chapter 4

Requirements for HSC-oriented roughing

When we speak of HSC-oriented CAM programming for rough machining, it must be understood that, above all, the technological aspects of a machining operation familiar in the past must be subjected to the scrutiny of CAM users whose outlook has been transfigured by CAD. Practical and economically feasible manufacturing is possible only if the programmer or specialist determines how the machining operation will be performed, based on knowledge and skills gained through experience. A modern CAD/CAM system must be capable of implementing the requirements and ideas of the user. In the future, experts must be in a position to define the machining operation on the basis of technological and production-engineering aspects, instead of being limited by the options provided by the CAM system, as is now the case.

In practical applications and in current literature, a constant offset following rough machining is considered to be an optimum prerequisite for HSC finishing. How to obtain this constant offset by way of a roughing or pre-machining operation is up to the NC programmer. Due to the absence or inadequacy of an up-to-date description of the metal blank, commonly used CAD/CAM systems do not furnish suitable support. A gap can be discerned all down the line in the machining description between roughing and finishing. CAD/CAM systems designed to generate HSC-compatible roughing programmes must have eliminated this shortcoming. Moreover, process-specific and technological aspects must be taken into account in addition to mathematical view-

points.

Once the available surface data for a later roughing operation have been prepared, various milling strategies can be applied to the part. In the process, NC path calculation is performed to a large extent according to purely mathematical regularities. Technological aspects, which each and every NC programmer surely tries to heed at the beginning of his or her career, recede behind the opportunities offered by the CAM system. In time, the programmer succumbs to the power of habit and begins to think within the limits imposed by the system. The consequence: programmes that often are dictated by the CAD system and that fail to take technological constraints into consideration. The better able the shop is to manage the supplied programmes, the more programmers in job planning distance themselves from familiar basic technological knowledge. It is precisely this situation that can be very critical for HSC-compatible roughing. HSC-oriented roughing exploits the performance limits of machine tools, spindles and milling cutters. Thus reserves are only conditionally available in this machining process. In order to obtain optimum production results, technological constraints must be taken into account when NC traverse paths are calculated. The CAM system must aid the programmer in this task by providing suitable prerequisites based on surface topography, blank specifications, workpiece material/cutting-media combinations and other parameters that consistently provide for favourable machining conditions.

Support in selecting suitable process parameters has been a dark chapter in the history of programmes for rough machining. Up to now, the CAD/CAM system leaves the selection of suitable cutting and feed parameters for the machining job to the operator, who must rely on knowledge gained through experience or on tables published by the various cutting-media manufacturers. Attempts to build manufacturer-neutral cutting-material databases have not yet been able to escape the bounds of a purely academic environment. So far, practical application in rough machining has failed due to the inability to transfer the stored process data. Optimum process parameters have been established on the basis of cutting trials usually carried out under laboratory conditions. It is not certain to what extent these constraints can be applied to a practical machining situation using a particular part. For this reason, these cutting-parameter databases are not as widely accepted as would actually be hoped. The job planner continues to rely on knowledge gained through experience when selecting

cutting-parameter databases for rough machining. In contrast to conventional roughing, there are no ample safety reserves available when designing process parameters if the advantages of HSC are to be applied to roughing. In some cases, even a minimal error in defining process parameters can quickly result in tool breakage or damage to the part. If the job planner does not possess adequate experience, he or she will tend to specify large safety allowances, hoping thereby to achieve a reliable and safe machining operation. No doubt, this does not ensure time- and cost-effective utilization of cutting-tool materials.

Despite the ever-expanding responsibilities of the NC programmer and the steadily growing demands on his expertise, less and less time remains for necessary concerns about programming. New and, above all fast technologies such as HSC roughing are being applied to reduce production times and increase productivity. For the NC programmer this means the provision of complex NC programmes associated with longer computing times accompanied by a simultaneous increase in machine availability brought about by a reduction of machining times. The only way to secure and expand existing knowledge gained through experience on a long-term basis is to develop CAD/CAM systems in the direction of technologically optimised NC machining systems.

In order to carry out HSC-compatible roughing of complex part geometries with the aid of a CAM system, milling strategies that take technological and economic constraints into account must be found and developed. To ensure widespread applicability, these strategies must then be implemented in easy-to-use NC functions.

The individual components that influence the results of the roughing process will be elucidated in the following. Requirements on the CAD/CAM system are derived from them.

4.1 Cutting tools

Cutting tools play a particularly dominant role in die, mould and pattern manufacturing. Tools-and thus cutting-tool materials as well-have a considerable impact on the cost of producing parts. Although tools account for only 2-5 percent of the total cost of manufacturing a part, tool performance has a major effect on production costs. For

example, machining time depends to a high degree on attainable cutting speeds. Tool life determines the frequency of tool changes and, consequently, unproductive idle time. Sudden tool breakage causes machine downtime. This list could be continued indefinitely. For this reason, materials for cutting tools have always been the subject of intensive research, whereby the objectives in developing cutting-tool materials have always been to improve performance in order to permit shorter machining cycles, expand the areas of application to reduce stock levels, and improve dependability and resistance to breakage in order to reliably exploit useful tool life and avoid machine downtime [33]. Fig. 4.1 graphically illustrates the development of cutting-material performance during the 20th century. It becomes evident that it has been possible to maintain a more or less constant improvement in attainable cutting capacity during the past 100 years. This is even more remarkable when one considers that the graph does not show the major, spectacular innovations in the cutting-materials sector during the past 30 years and thus it is more the small, inconspicuous improvements that have sharply enhanced cutting-material performance.
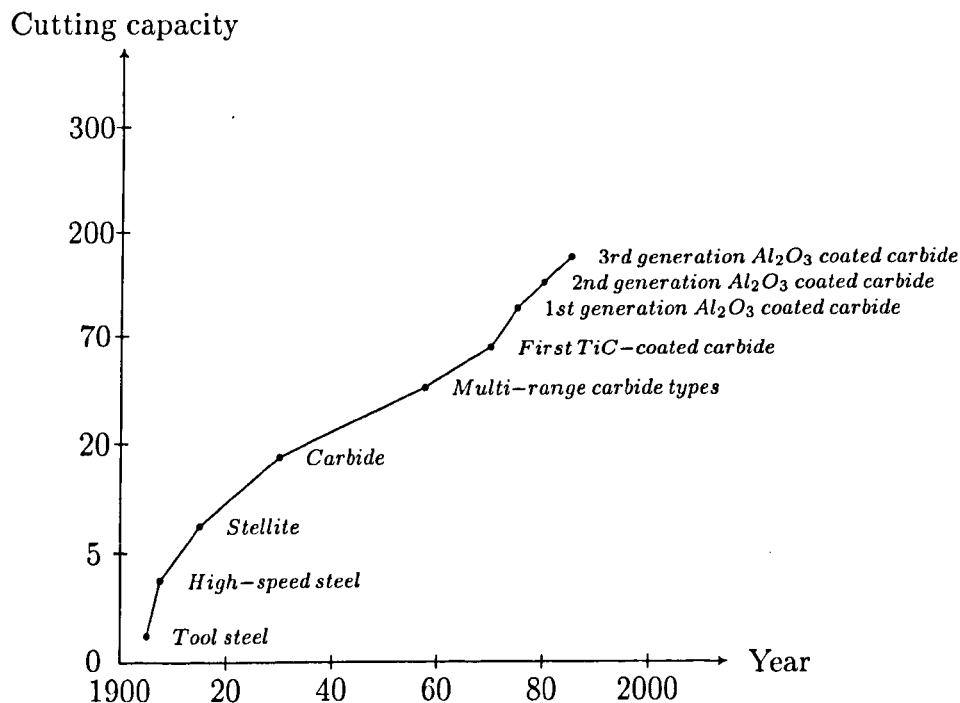
Figure 4.1: Increase in stock-removal capacity due to cutting-material development

The two main properties that largely describe the behaviour of cutting-tool materials are hardness or abrasion resistance on the one hand, and toughness on the other, whereby as a rule, the price paid for an increase in wear resistance is a loss of toughness and vice versa. Hence the selection of a suitable cutting material always represents a compromise in which the proportions of hardness and toughness should be optimally balanced for the respective machining job. The demand for increased toughness and hot abrasion resistance of the cutting material essentially stems from the dynamic load exerted on the cutting-edge and the high processing temperature typical of the roughing process.

One development of considerable significance was the introduction of coating technology in the late 1960s. For the first time, it was possible to at least partially eliminate the compromise between the toughness and hardness of a cutting material. Coatings made of TiN, TiCN and Al_2O_3 are widely used. Such tool coatings made it possible to provide a relatively tough base or substrate with a super-hard coating that assumes responsibility for wear resistance. Moreover, special ceramic coatings such as Al_2O_3 also exhibit excellent resistance to the effects of heat and are therefore also highly suitable for use at high cutting speeds. The development of modern cutting materials created potential for increasing cutting speeds without sacrificing tool life.

Rough machining in die, mould and pattern manufacturing produces a large number of highly diverse parts made of every conceivable material. Thus selection of the ideal cutting material/workpiece material combination always depends on the individual machining task. The individual cutting materials will not be dealt with in detail here, since this would exceed the scope of this paper.

The selection of different types of tool designs for roughing affects expenditures of time and cost as well as the geometry reaming after roughing. In roughing in layers the remaining residual offset varies considerably as the depth of cut remains constant, depending on the angle of inclination and the cutter used.

The cylindrical end mill is superior only in very steep wall areas. In all other areas, the part to be produced can be approximated with considerably better accuracy using torus-type cutters. The torus mill gives the best results with respect to the generated offset situation. The circular design of the reversible carbide tips permits closer approximation of the final contour of the part. In this way the positive characteristics

of a spherical cutter in terms of superior trueness to contour are also utilised for the higher-capacity torus mill. The cylindrical end mill exhibits extremely unfavourable characteristics, particularly for machining inclined surfaces. In addition to the much higher maximum offset, a stepped surface topography is formed that may have an adverse effect on the subsequent finishing operation (Fig. 4.2).
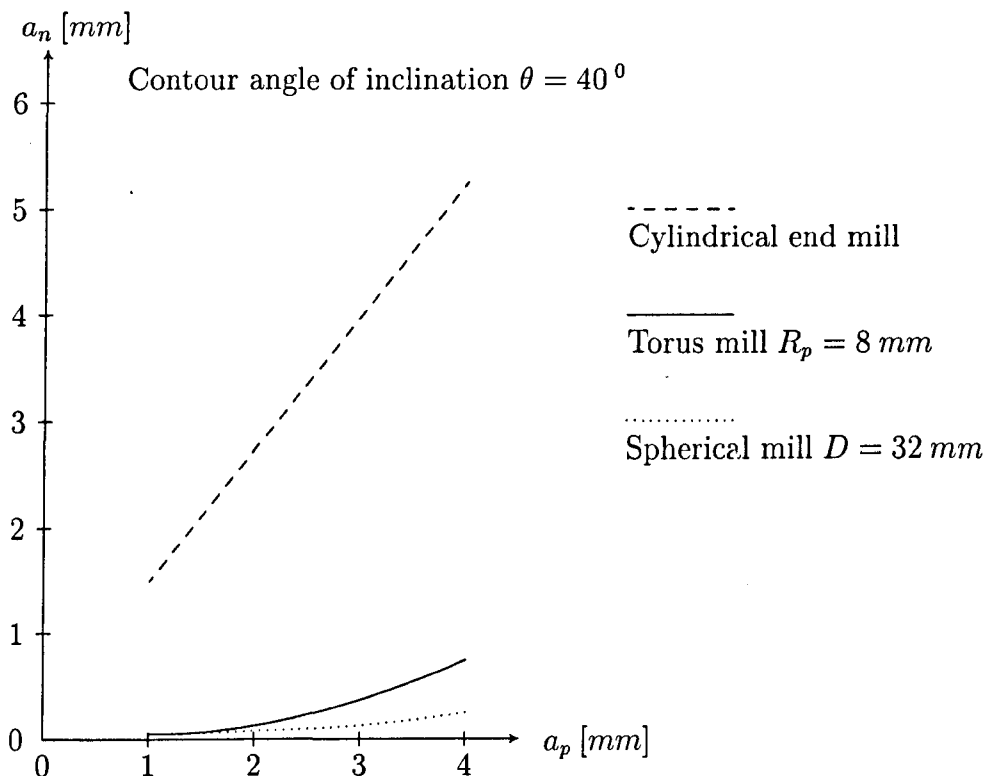
Figure 4.2: Maximum residual offset as a function of cutter geometry

The best results can be obtained using torus mills because higher values can be selected for the process parameters depth of cut a_p, contact width a_e and feed per tooth f_z than are used with cylindrical end mills and ball-end mills. Table 4.1, in which examples of the obtainable rates of metal removal of the three cutter types under identical marginal process conditions are compared, also illustrates this.

Moreover, the torus mill also offers distinct advantages over cylindrical end mills and ball-end mills with respect to process reliability. One the one hand, the arrangement of the tips avoids the face cut at zero cutting speed that is critical for spherical cutters. On the other hand, the large tip radii have an advantage over the cutting edges of the cylindrical end mill, whose corners tend to break out.

Cutter type	Attainable rate of metal removal
Torus mill	$138.75 \ cm^3/min$
Ball-end mill	$31.5 \ cm^3/min$
Cylindrical end mill	$108.0 \ cm^3/min$

Table 4.1: Rates of metal removal attained by various cutter types

For these reasons and the opportunity to use cost-effective reversible carbide tips, the application of torus-type cutters with reversible inserts has proved itself in the rough-machining sector. The circular reversible tips avoid the previously mentioned load on the cutting edge corners that occurs with square tips and, what is more, provide the maximum amount of leeway in designing the load on the cutter and spindle and thus on the machine tool. Circular reversible tips permit high feed values and thus high machining speeds. Moreover, these cutters are highly stable and can implement a large diameter. The application of reversible carbide tips makes it easy to adapt the cutting material and cutting-edge geometry to the workpiece material. Because the reversible tips are not reground, they always exhibit high geometric accuracy.

Conventional HSS end milling cutters, with or without a corner radius, are mainly used for machining soft workpiece materials or when cutters whose diameters do not permit the attachment of reversible tips are required. Spherical cutters are used only for the second roughing procedure or for soft workpiece materials.

4.1.1 Cutters in the CAD/CAM system

Conventional CAD/CAM systems provide only limited support for selecting tools. The tools can be stored in libraries together with their geometric parameters. In most cases, the user must spend much time and effort to create and maintain such a library. This task is performed exclusively via the interactive interface of the CAD/CAM system. Database-supported tool management systems are seldom encountered in practical NC programming due to the lack of standardised interfaces to CAD/CAM systems. When available, they are system-specific links implemented either by the user himself or the cutter manufacturer.

The CAM system should not leave the user alone to select the milling cutter for a specific machining task. Rather it should suggest a proposal for selection based on

criteria such as economy, contour approximation, etc. However, this requires exten-
sive computations. Thus either far-reaching simplifications, such as those used by
Mizugaki [25] in his process for automatic determination of the milling cutter, must
be implemented, or cutting zones and, if required, cutting distances must be pre-
calculated and evaluated according to the selected criteria for every tool in question.
This is not yet feasible using the computing power available today and concerns the
topic of process planning. Becker [2] describes basic concepts for this.

Geometric tool data

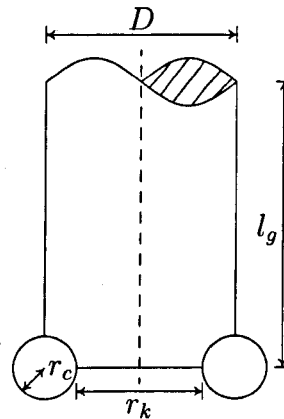Fig. 4.3 shows a schematic representation of cutter geometry.

Figure 4.3 Geometric cutter data

The following geometry-related tool data are the minimum required for rough ma-
chining:

- Tool ID number

- Diameter D

- Corner radius r_c

- Core radius r_k

- Projecting length l_g

Cutter diameter, corner radius, core radius and maximum projecting length are assigned to a tool ID number. This allows representation of the geometries of spherical, torus and cylindrical end milling cutters. As described above, other cutter geometries exhibit disadvantages for roughing in layers and are used in practical application either only in exceptional cases or not at all. A cutter must never be used for purposes contrary to its specification. Some torus-type cutters with reversible carbide tips cannot beyond the centre. For this reason, it is necessary to specify a core radius, which is taken into account when determining cutting zones. If cutting zones were too small, stock beneath the centre of the cutter would not be removed. This would inevitably cause a collision that would result in damage to both the cutter and the part. The minimum area of permissible cutting zones can be determined with the aid of the core radius parameter. The limits of application of a cutter for machining deep parts are defined by specifying the maximum projecting length.

Technological tool data

The following process-related tool data are the minimum required for rough machining:

- Workpiece materials

- Cutting materials

- Speed

- Feed rate

- Tool-entry strategies

The available cutters are classified according to the materials to be machined. This approach allows a direct allocation of workpiece material-cutting material combinations. The optimum feed rate is based on the maximum exploitation of the depth of cut a_p and width of cut a_e specified by the user. Under other contact conditions, the system should adapt feed settings dynamically. The machining parameters must be defined, contingent on the projecting length, in such a way as to minimise the risk of

process instability and/or deviations of dimensions and shape that may occur due to anti-penetration forces.

Depending on the properties of the milling cutter, it should be possible to indicate up to three methods, together with their parameters, as tool-entry strategies. The illustrations in Fig. 4.4 show the three tool-entry strategies and their characteristic geometric and process parameters.

Type A: Drilling   Type B: Ramp-feed

Type C: Spiral-feed
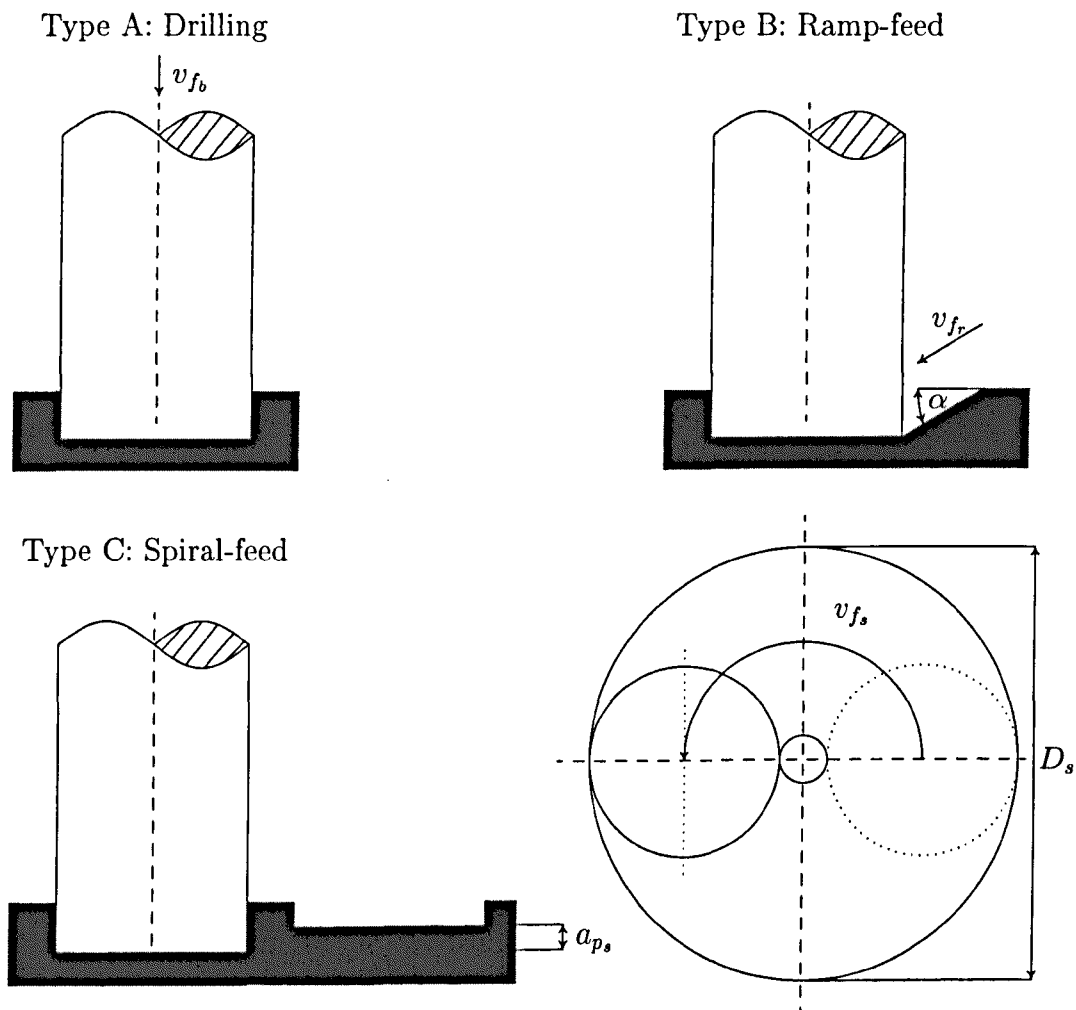
Figure 4.4 Tool-entry strategies

The feed rate value v_{fb} in the direction of the drilled hole is indicated for the drill-type entry procedure (type A). The procedure for ramp-shaped entry (type B) is characterised by a maximum entry angle α and the feed rate v_{fr}. Spiral entry (type C) is assigned the parameters circular path diameter D_s, the maximum feed per circu-

lar path a_{ps} and the corresponding feed rate v_{fs}. The CAM system must take the specification of the cutter (e.g. limited plunge-cutting capabilities) into account when tool-entry procedures are calculated. Cutters without plunge-cutting capabilities cannot feed down into the stock and thus must feed outside the workpiece. This means that the cutter must leave the material and then enter it again. Such entry-exit operations drastically minimise tool life. Cutters with plunge-cutting capabilities have a longer useful life if they are in permanent engagement. For this reason, these cutters should always feed while in the material. One advantage of ramp-feed over drill-type tool entry the formation of considerably shorter chips, which can easily be removed from the produced groove. On the other hand, steep infeed motions produce long snarl chips that are repeatedly pulled back into the cut, considerably jeopardising process safety due to the risk of disastrous breakage of the tool's cutting edges.

The tolerance range for tool-entry parameters is very limited, particularly for machining high-strength materials with the aim of HSC-oriented roughing. Thus optimum definition of the process parameters is a prerequisite for the stability of the process. In this respect, the specification of material strength is by no means limited to high-strength materials. The opportunity to use mechanical strength properties to characterise materials makes it possible to specify optimally adapted process parameters for machining other materials as well, e.g. graphite or plastics. Another benefit of this extensive recording of data is the ability to adapt flexibly to specific in-company conditions. Internal company know-how can flow via optimum process parameters directly into automatic NC calculations, ensuring efficient rough milling of blank parts.

4.2 Entities

4.2.1 Part

The product spectrum for the die, mould and pattern manufacturing sector is highly diverse, ranging from cars and accessories, household appliances, toys, foodstuffs and electrical and electronic devices to ships and aircraft. The surfaces of these products are not usually developed from simple, regular basic shapes. The required functionality or design often permits only surfaces that can be described analytically solely

with a great deal of effort or not at all. Only simplified, approximated 'backup surfaces' can be realised here. Thus characteristic of such product ranges is that free surfaces dominate in product design. This allows the products to satisfy the requirements placed on them with respect to style, i.e. aesthetic and functional aspects. These parts are subdivided essentially into models, forging dies, injection moulds and pressure die casting moulds, deep-drawing dies and cutting tools. In accordance with the mechanical and thermal loads exerted on them during use, forging dies exhibit mechanical strength properties clearly surpassing those of injection and pressure die casting moulds. Tensile strengths of 2,000 N/mm^2 are not unusual. In particular the high alloy content in the steel and grey cast iron materials aggravates cutting conditions for machining deep-drawing dies. The complexity of the contour to be generated is a further characteristic of the respective part groups. Whereas forging and deep-drawing dies exhibit numerous slightly curved surface areas with relatively large curvatures, injection and die casting moulds have a highly filigree-structured character with, in part, very deep engraving. In summary, it can be said that both the geometry and the material of the parts to be produced in die, mould and pattern manufacturing are highly heterogeneous. In practical application, the production of these parts remains a highly demanding task. By no means can a part's geometry be modelled exclusively by means of ruled surfaces or solids, as is usually done in research projects in the academic world; on the contrary, free surfaces are used.

4.2.2 Blank

The production of a part always begins with a blank. The blank may contain the entire part to be produced or, in the case of repair or overhaul tasks, it may be situated only in an area of the part. In a majority of all parts, a cuboid or pre-cast blank is available. However, variations of these two standard blanks are steadily expanding at present due to economic and technical reasons.

Cuboid blank

The simplest form of a blank is the parallelepiped or cuboid. The cuboid may consist of one or more blocks of materials. Because the cuboid does not usually even approximate the shape of the part to be produced, a great deal of stock must be removed

during the milling process. Injection moulds, small parts or soft workpiece materials are application areas for the cuboid blank.

Precast blank

The precast blank already closely approximates the later finished part. The casting is made with the aid of an expendable pattern, whereby a blank made of Styrofoam is encased in sand and the workpiece material is then poured in. The result is a casting, but the Styrofoam blank is lost. However, due to shrinkage, modifications of the part to be produced or defects in manufacturing the blank, the casting does not always have a constant offset. Using today's manufacturing techniques, in which the casting is often designed as a CAD model, attempts are being made to rule this out to a large extent. The cast blank is used primarily for manufacturing large dies, blanking and punching dies and sheet-metal dies.

Special blank types

A block of material often has areas that are situated entirely outside the limits of the part to be produced. These areas are cut out by means of some preliminary treatment, e.g. sawing or manual milling. The blank may already exhibit a complex geometry as a result of this step in production.

The final variation of the metal blank is a combination of a precast blank and hardened steel jaws permanently screwed to the casting. Production-engineering considerations, e.g. wear or severe forces caused by deformation require the use of such jaws.

4.2.3 Entities in the CAD/CAM system

To apply the requirements imposed on an HSC operation to rough machining and create potential for optimisation as a result, the virtual system must have complete and exact knowledge of the metal blank and the part. While representation of the part is familiar to nearly all NC programming systems in the form of a 3D design, the geometry of the blank is often inadequately approximated. As a rule, blank geometries that deviate from the standard geometries (parallelepiped and cast blank) can hardly

be represented. If geometries are not sufficiently known, the CAD/CAM system cannot, for reasons of safety, extend the technological interpretations (e.g. cutting parameters) of the NC programmes to exploit the load limits of the material and machine tool. Improvements in this area are possible only if the CAD system is able to provide the NC programmer with problem-oriented proposals for setting optimum process parameters. However, this requires the ability to describe the machining job in a way that makes safe, computer-assisted calculation of process parameters possible. Accordingly, a virtual model must exist that is capable of imaging the process-related constraints and relationships of the machining process at any time. The basis for this is an adequate description of the part and metal blank. The conventional method, the surface-based description of part and blank geometries, is certainly no longer sufficient for this new task in NC programming. On the contrary, it is necessary to develop mechanisms for modelling interim workpiece conditions, because the only way to compute stock-removal capacities, and derive optimum cutting parameters from them, is to have knowledge of the current state of the workpiece.

Problems arise in the most diverse locations during the manipulation of free surfaces in die, mould and pattern manufacturing, where surfaces must be generated and further processed by a wide variety of systems. First the surfaces must be transformed into a usable quality. On the one hand, this is necessary due to the number of different surface modellers that have participated in the geometry description and, on the other hand, to loss of quality through interfaces and, in particular, as a result of inferior designs developed in part under pressure to meet deadlines. According to an international survey of die, mould and pattern manufacturing companies reported by Trampler [32], only some 15 percent evaluate data quality as good. The remainder rate it as acceptable or poor. The number of surfaces that describe a part or blank may amount to several thousands. Such surfaces must describe the geometry completely, correctly and in a production-oriented manner. Frequently encountered problems include gaps between surface segments, overlapping surfaces, very close concave round-of radii and lack of accuracy in the part or blank description. However, CAM systems must be able to cope with the reduced data quality and must not make it necessary for the NC programmer to carry out extensive data editing. But in practical applications, data stemming from the company's design department are usually either not suitable for manufacturing or must be supplemented with appropriate add-on constructions. On the average, it can be said that an NC programmer spends approximately two-

thirds of his or her time in editing and supplementing data, while actual programming accounts for only one-third of total time. Therefore, a CAD/CAM system for die, mould and pattern manufacturing must make it possible to produce add-ons easily and largely automatically with the aid of individual CAD functions.

The system should also support the user in designing blank geometries. In addition to all the standardised design options in the CAD environment, there must be functions available that can be used to design the geometry of a blank completely within a short time. To design a cuboid blank in the CAD system, the system must automatically calculate a box around the indicated part surfaces. The user should be able to enlarge or reduce the size of the box. For the design of a cast blank, the system generates the blank with the aid of part surfaces and casting offsets assigned to them. This makes it possible to assign different offsets to individual areas of the part. Because an increasing number of blanks are being designed with CAD and supplied together with the part design, these data must also be capable of being loaded from an external file. In actual practice, a finished metal blank is already available in the shop. However, it is unknown to the virtual world of the CAD/CAM system. In this case, digitising with the aid of subsequent surface modelling furnishes an opportunity for blank design. In this technique, the blank is computer-scanned and the data thus obtained are buffered. This computerized image of the physical blank is then available in the form of a large number of densely packed discrete points. To avoid exceeding the memory capacity of the CAD/CAM system, the data must be reduced with a minimum loss of information and converted into a suitable surface representation (e.g. mesh).

4.3 Roughing layers

Process reliability is a fundamental prerequisite for cost-effective rough machining. Roughing strategies are the most important basis for organising a reliable roughing process. Here, the location, size and shape of the chip at initial approach are responsible for the load exerted on the cutter and the cutting edge.

Multiple strategies are available for roughing a part. Different strategies are selected based on part geometry, the metal blank and in-company philosophy. The standard procedure is roughing in layers. In addition to a high degree of process reliability, the

benefits of this strategy are large stock-removal capacities with high feed rates and the ability to use advantageous milling cutters. The cutter is guided along horizontal clearing layers at a constant cutting depth. The layers serve as a basis for calculating cutter fields in each machined layer. The blank and part geometries are cut on the z-profiling planes in which machining will take place. The resulting contours represent the borders between the material to be removed and that which will remain. Thus the prerequisite for the roughing in layers strategy is prior definition of the roughing layers.

4.3.1   Roughing layers in the CAD/CAM system

In contrast to three-axis finishing programmes, roughing in layers produces plane milling paths instead of three-dimensional ones. The user must define roughing layers for this purpose. Several options are available for defining layers. A layer batch may be selected in the CAD file. Specifying the machining zone with a minimum and maximum z value and indicating a number of layers is also conceivable. However, the user prefers a different, very simple method for defining layers that will be described below. Moreover, there are yet other requirements on the system. These will also be mentioned.

- Layers are defined by specifying a minimum and maximum z value and the desired depth of cut on z. Here the machining zone corresponds to a limitation of the tool root. The system proposes the depth of cut based on the selected cutter.

- If the height of a part requires roughing with two cutters of different lengths, it must be possible to define multiple machining zones with different depths of cut.

- Ideally the system automatically searches for the deepest layer, taking the shank length of the selected cutter into account.

- The system should develop the layers automatically from bottom to top. This ensures that no offset remains at the minimum z elevation.

- The system should also be capable of detecting plane surfaces and defining a layer at their elevation. The vertical feed no longer needs to correspond exactly to the specified value; it may be reduced by the system.

4.4 Clearing strategies for cutter fields

As described in Chapter 2.4, roughing in layers produces cutter fields in each machined layer. These fields must be calculated automatically by the CAD/CAM system. A field is delimited by one or more boundary curves. The boundary curves correspond to cutter axis paths on which the tool has contact with either the blank or the part. Curve segments in which the cutter is in contact with the blank are called blank contours. Blank contours delimit the machining area in a plane. Curve segments in which the cutter is in contact with the part are called part contours. Part contours subdivide the entire machining area delimited by the blank contours into areas to be machined and areas to be excluded from machining. The actual part, which, of course, must not be violated, is situated within the areas that are excluded from machining.

A boundary curve may consist of only the blank contour, only the part contour or of blank and part contours. These curves enclose an area containing stock that must be removed by the cutter with a constant depth of cut. Thus the task is to generate a horizontal distribution of milling paths for these cutter fields that satisfies the technical requirements on the HSC rough machining process.

4.4.1 Process-related requirements

The requirements necessary to maintain process stability derive from the widely differing loads exerted on the tool cutting edges. These loads have an impact on the life of the cutter. The contact conditions determined by the process parameters type of milling (climb/conventional) and overlap a_e/D (Fig. 4.5).
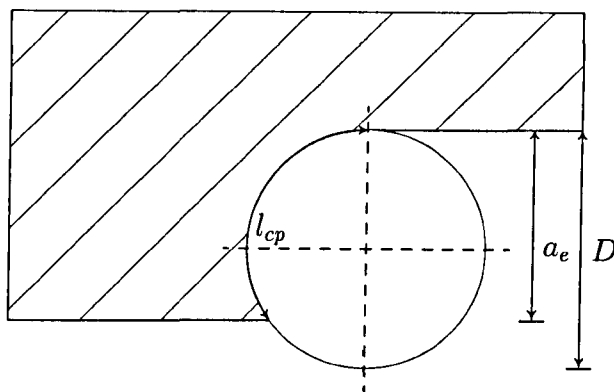
Figure 4.5: Overlap a_e/D and length of cut curve l_{cp}

Tool life

By tool life T is meant the cutting time in minutes from grinding until the tool becomes dull under existing cutting conditions [19]. The limits of tool wear, a change in the shape or surface finish of the workpiece or a change in cutting force, cutting temperature or chip formation may be selected as criteria for determining tool life. Values for tool life can be determined in long-term trials. In theory it is difficult to make an accurate statement about the life of a tool because it depends on numerous factors. Causes of wear include an excessive spindle speed that the cutting edges cannot withstand, a too heavy feed that causes the edge to break off, inadequate or irregular cooling which causes cracks in the cutting edges, or vibrations at the cutting edges that cause them to break off. In addition to the cost of replacing the cutter or the carbide inserts, other economic disadvantages are incurred due to machine downtime. To change a cutter, the milling machine must be stopped, and the cutter must be unclamped and perhaps re-sharpened. A re-entry procedure must be performed when the cutter is re-clamped. All these measures can be very time-consuming and diminish the economy of the production process. Thus there is a very obvious demand to rule out factors that minimise tool life.

The aim of high-speed roughing is to remove material at a high speed. This requirement must go hand in hand with the economic necessity to maximise tool life. To maintain feeds, contour characteristics must be harmonious and must no include any tangentially discontinuous transitions. Even very small radii in the milling paths have

a negative influence. Paths that are not tangentially smooth and small radii cause the machine control to reduce feed or even stop the machine suddenly. This subjects the entire kinematics of the machine to very severe forces and accelerations. A reduction in feed prolongs the total traversing time of a milling programme. In addition to the very heavy load exerted on the machine and the extended traversing time, discontinuous tool travel has a particularly negative effect in terms of minimising cutter life.

Resultant forces are exerted on the cutter while it is in contact with the material. In climb milling, the cutter tends to be pushed away slightly from the work. If the cutter comes to a sudden stop, and is no longer in contact, the resultant forces are no longer active. This also cancels the out the minimal distortion of the cutter, which results in minimum tool contact. The cutter rubs against the part and the heat generated cannot be carried away by chip. This condition quickly leads to heating of the cutting edges, which in turn diminishes tool life. Upon accelerating again, the cutter is in complete contact, which causes a very heavy load on the cutting edges as a result of impact forces (Fig. 4.6).
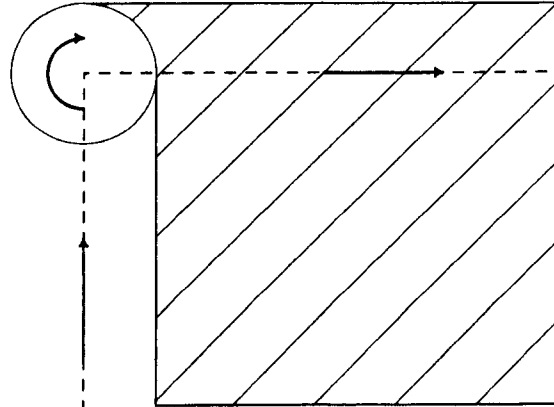
Figure 4.6: Contact conditions in tangentially discontinuous milling paths

However, tangentially discontinuous paths and small radii can be avoided at any time by inserting a radius. The minimum size of the radius at which feed is reduced only insubstantially or not at all depends on the respective machine control system and, therefore, should be a freely definable parameter. In the following, the elimination of tangentially discontinuous milling paths and small radii is considered an absolute prerequisite and, therefore, will not be dealt with in more detail.

The entry and exit cuts, during which the cutter enters and cuts free of the material, respectively are particularly significant. Paulus [27] discovered that the shock exerted when the cutter bites into the stock and the shock exerted when the cutter leaves the material both minimise tool life. Paulus recommends achieving the optimum contact cross-section as quickly as possible or to leave without each of the tool's cutting edges having to too frequently accommodate rapid and major changes of the chip cross-section. Kölling [23] offers a specific proposal by which he investigates the circular entry cut as advantageous for tool wear (Fig. 4.7).
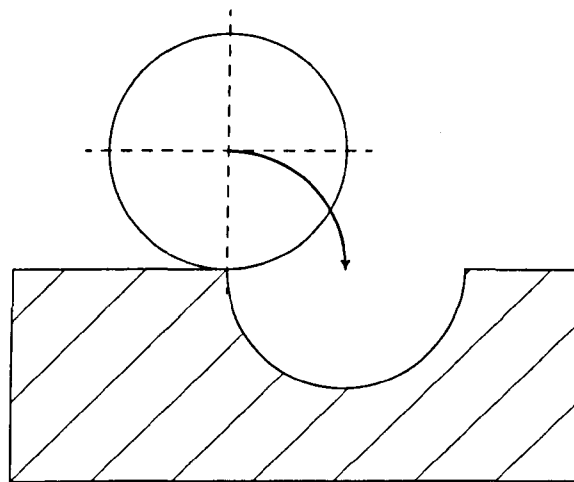
Figure 4.7: Circular tool entry according to Kölling [23]

Moreover, a shallow plunge-cut at a plunge-angle permitted by the cutter specification provides a high degree of process reliability. However, all variations only minimise wear of the tool's cutting edges. Avoiding entry and exit cuts prove to increase tool life. Tool motions that take place in the open extend the total distance traversed. Continuous engagement in the material is beneficial for tool life and minimises tool travel. If the cutter must be withdrawn, it should not return to the retract plane. Taking a current blank geometry into account, the system should automatically determine local cutter withdrawal. Automatic determination of evasion strategies would also be desirable. This is practical in cases where a tower is situated, for example. For this however, it will be necessary to check the toolholder and head, in addition to the cutter with its shank length, for collision with the current blank. Another way to suppress retracts is to specify a connection length between cutting zones. If the 2D connection between two zones is less than the defined length, a collision-safe traverse motion is carried out

on the current blank. Multi-level, instead of a layer-by-layer, machining of cutting zones in pockets and around domes provides a further opportunity to avoid cutter entry and exit into and out of the material (Fig 4.8).
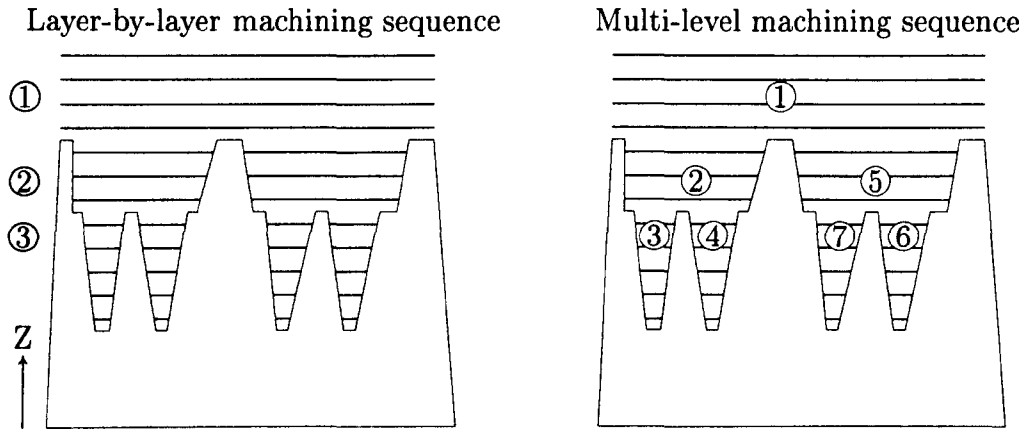
Figure 4.8: Layer-by-layer and multi-level clearing

Since the total distance traversed consists of cutter movements in the material F_{in} and movements outside the material F_{out}, the following condition must be satisfied when a cutter field is cleared out:

$$\int^s F_{in}(s) >> \int^s F_{out}(s) \qquad (4.1)$$

Types of machining operations

Historically, conventional milling was the first milling process applied. The cutter rotates in a direction opposite to the translation of the part (Fig. 4.9). The cutter's teeth scrape the material until the resistance between part and cutter is overcome and the cutter bites into the material. From this point on, each cutting edge begins to cut, separating a comma-shaped chip from the material. At the start of the cutting process, the chip thickness $h_e = 0.0$, and reaches its maximum size just before the cutter tooth leaves the material.

In climb milling, the directions of cutter rotation and workpiece feed are identical (Fig. 4.9). Each cutter tooth in contact immediately bites into the solid material. The maximum chip thickness is reached immediately following penetration by the

tooth and then tapers off to zero. The result is that friction diminishes to zero, in contrast to conventional milling. The work is pressed against the worktable, not lifted away from it, as may occur in conventional milling.

Conventional milling   Climb milling
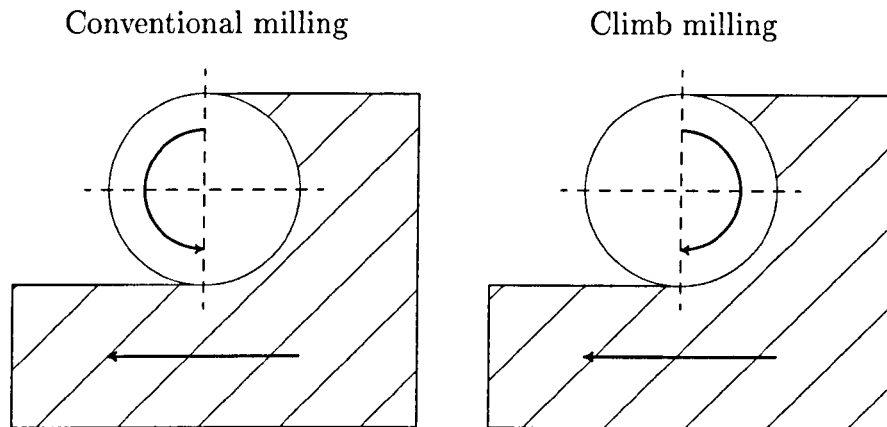
Figure 4.9: Conventional and climb milling

As described by Bieker [4], the tool life travel achieved for overlaps $a_e/D > 0.5$ with conventional milling is distinctly shorter than with climb milling. The increased wear in conventional milling is a result of splintering off of micro-particles from the periphery of the cutting edge that are then flushed out as the cutting distance increases. Because climb milling also results in splintering of the cutting edges with smaller overlaps due to adverse contact conditions, there is no significant difference in tool life travel for $a_e/D < 0.4$. Earlier investigations [8][24] have also demonstrated that cutter-exit conditions in milling have a considerable effect on tool life characteristics. The loss of tool life travel observed in conventional milling is attributed above all to tensile stresses that build up in the cutting edge when the tool leaves the material, causing particles to break off. The friction and compression forces produced when the cutter bites into the stock with zero chip thickness in conventional milling also reduce tool life. Parallel to the tool face, strong shearing stresses are induced in the transition between the cutting edge and flank. Together with the stresses caused by cutter entry and exit procedures, these forces contribute to an increase in wear progression [4]. The adverse effects of the entry and exit conditions in conventional milling are aggravated when unstable tools, like those required for roughing deep very finely sectioned parts, are used. This can be attributed to deflection of the cutter when it strikes the material, which delays the start of chip formation, thus increasing

the frictional stress exerted on the cutting edge, and can result in breakage of the tool's cutting edge within only a few millimetres of cutter travel.

Therefore for rough machining parts, it may be inferred that climb milling produces a smoother cut and exerts less load on the cutting edge when the cutter enters and leaves the material than is the case in conventional milling. Climb milling proves to be an advantageous milling technique due to the uniform flow of chips, which ensures safety against splintering off of the cutting edges, and lower maximum values for cutting force components.

The rate of metal removal $Q(t)$ consists of a climb-milled portion $(C_d(t))$ and a conventionally milled portion $(C_u(t))$. Hence the rate of metal removal results from:

$$Q(t) = C_d(t) + C_u(t) \qquad (4.2)$$

With respect to useful cutter life, conditions are most favourable when time-cutting volume consists of only a climb-milling portion; hence the following applies:

$$Q = \int_0^t C_d(t) \qquad (4.3)$$

However, an absolute prerequisite for clearing cutter fields in high-speed roughing operations is that the share of conventional milling never exceeds the share of climb milling and thus the following applies at all times:

$$C_d(t) >= C_u(t) \qquad (4.4)$$

If the shares of climb and conventional milling are equal, the milling cutter is in full engagement. If a part contour is traversed with the cutter fully engaged, care must be taken to ensure that climb milling is used to remove the material toward the part. The reason for this is distortion of the cutter. As described above, the cutter is always pulled into the material in conventional milling. In the case of long, narrow cutters, this deflection can lead to contact with the part contour.

Overlap

One reason for the breaking off of material from the periphery of the cutting edge, which occurs more frequently when contact widths are smaller than the cutter radius, is increased alternating thermal loads. This is due to the low ratio of cutting time to cooling-off period per cycle in conjunction with the mean chip thickness (e.g. 40% of the maximum value at $a_e/D = 0.1$), which is still relatively high even with smaller contact widths. However, the contact conditions upon penetration by the cutting edge are of even greater significance. When it cuts out a chip, the cutting edge penetrates the workpiece material through impact against the part, cuts out the chip along a circular cutting path and then leaves the work. According to Beckhaus [3], contact conditions in milling are considered critical when the vulnerable cutting edge first penetrates the part and therefore must accommodate the entire impact load. Particularly in the case of tools used for high-speed roughing, it is important to know that tool cutting edges are highly sensitive to intermittent shock loads. The force of the impact has a considerable effect on dulling of the tool's cutting edge. To reduce the force of impact, initial contact between the cutting edge and the part should occur at a location within the face of the cutting edge. As analysed by Bieker [4], the area of the cutting edge in which adverse contact conditions prevail expands with diminishing overlap. In the case of radial contacts widths of $a_e > D/2$ only tool face contacts remain that provide for a harmonious distribution of the impact load. In addition, the cutting forces of the individual cutting edges are equalised by different directions. In this way, no brief, pulsing forces that result in vibration and chatter between the tool and workpiece are stimulated. On the contrary, the cutting forces are shallow and harmonious, resulting in soft entry of the cutter into the material.

The increase in the length of the circular path l_{cp} with large overlaps results in a reduction of tool life travel as a consequence of the higher effective friction path of the cutter. However, because stock-removal capacity increases with an increase in the radial contact width, tool life reaches a maximum at overlaps of $a_e/D > 0.6$ for machining commonly used workpiece materials in die, mould and pattern manufacturing. Neither verifiable theoretical findings nor practical investigations exist to support this statement. Instead, a ratio of tool life to overlap was assumed (Fig. 4.10) based on extensive data acquired from practical applications and will serve as a starting point for the following.
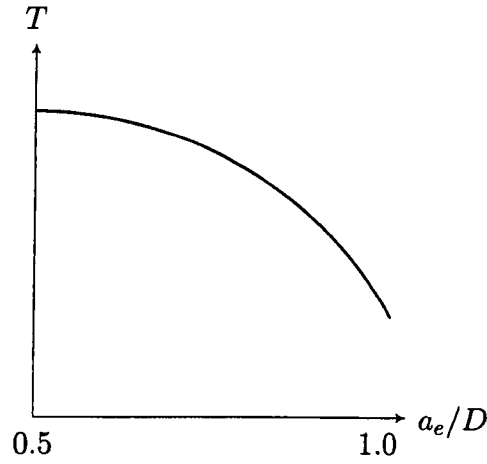
Figure 4.10: Tool life T in proportion to overlap a_e/D

The system can automatically optimise the position of milling paths in a cutting zone so that the cutter is constantly in engagement on all paths. To achieve this, the specified feed adjustment may be reduced, which prevents the final path from consisting of only a narrow web.

4.4.2   Target functions for clearing cutter fields

The following target functions for clearing cutter fields can now be summarized from the above process-related technological requirements:

$$\int^s F_{in}(s) >> \int^s F_{out}(s) \qquad (4.5)$$

$$C_d(t) >= C_u(t) \qquad (4.6)$$

$$a_e(t)/D > 0.5 \qquad (4.7)$$

4.4.3 Adapted feed

A cutter encounters critical contact situations when offset conditions are irregular or in the case of complete cutter wrap. Large fluctuations of the offset or irregular tool wrap represent a high risk in terms of process reliability in the rough operation. The danger of cutter breakage increases, particularly when slender cutters are used [30]. To remedy this, largely uniform loading of the cutter should be achieved during machining. The angle of wrap of the material around the cutter can be maintained at a relatively constant level by applying the milling strategies described above. However, the local offset situation must also be taken into account when the NC data are generated. In actual practice, such data are not constant, but instead, variable due to the geometric design of the part and the pre-machining steps carried out in advance. At constant rates of feed, peak forces exerted on the cutter and the resulting increase in wear, including tool breakage, are the consequence of fluctuating stock-removal capacity [15].

In practical applications, the increased loads are either tolerated and the machining operation is carried out at maximum speed under constant supervision by the specialist at the milling machine, or a lower feed rate is programmed that is oriented toward the maximum load. The great disadvantage of both of these approaches lies in the fact that HSC-oriented roughing can be applied only to a very limited extent under such condition. Prompt intervention by the operator in the case of locally increased offset is virtually impossible due to the desired high rates of feed. Although reducing the machining speed in advance for the entire operation increases process reliability, it impairs the economy of the process. Therefore, a CAM system that calculates NC paths for rough machining must adapt the rate of feed to local contact conditions. The CAM system must be able to reproduce at any time the momentary complex volume track left by the cutter in the part. This ensures that the shape of the part, which changes constantly during the machining operation, is known at any given time. The current shape of the part is the basis for calculating the cutting situation. The momentary rate of stock removal, as well as the distribution of the material relative to the tool, must be analysed and then used to determine current cutting forces. The data thus acquired serve to adapt the rate of feed to accommodate the current load exerted on the cutter.

To avoid excessively heavy peak loads the system must reduce the feed so that critical areas are traversed more slowly. Since this prevents the occurrence of inordinately heavy loads on the cutter, process reliability increases and rates of feed that reduce machine operating time can be used. The result is a more stable and reliable roughing operation that can also be carried out without human intervention.

4.5 Residual stock

The geometry of the part and the blank form a basis for laying out the process. The geometric constraints of the milling cutter (diameter and type) as well as the machining parameters are determined by way of the volume of material to be machined and the intricacy of the contours. In addition to these fundamental specifications, the residual offset left on the cutter following each individual machining step must be taken into account when the process is generated to avoid overloading the cutter in the subsequent machining step.

Depending on the cutter and the specified parameters, the blank, following one or more roughing programmes, still lacks the appropriate shape required to proceed to the finishing operation. A stepped or wavy residual offset still remains on the work. Pockets or beads are still completely filled with material. To conclude the roughing operation satisfactorily, these characteristic geometric areas must be analysed and tool- and process-specific parameters adapted to the task at hand.

4.5.1 Residual offset for roughing in layers

Zander [34] describes how, regardless of cutter diameter, a stepped or wavy residual offset forms, which depends on the selected radius of the cutting tip, the axial depth of cut and the angle of inclination of the part. Fig. 4.11 illustrates these geometric relationships.

	Influence of angle of contour inclination	Influence of cutting tip radius
Stepped residual offset		
Wavy residual offset		
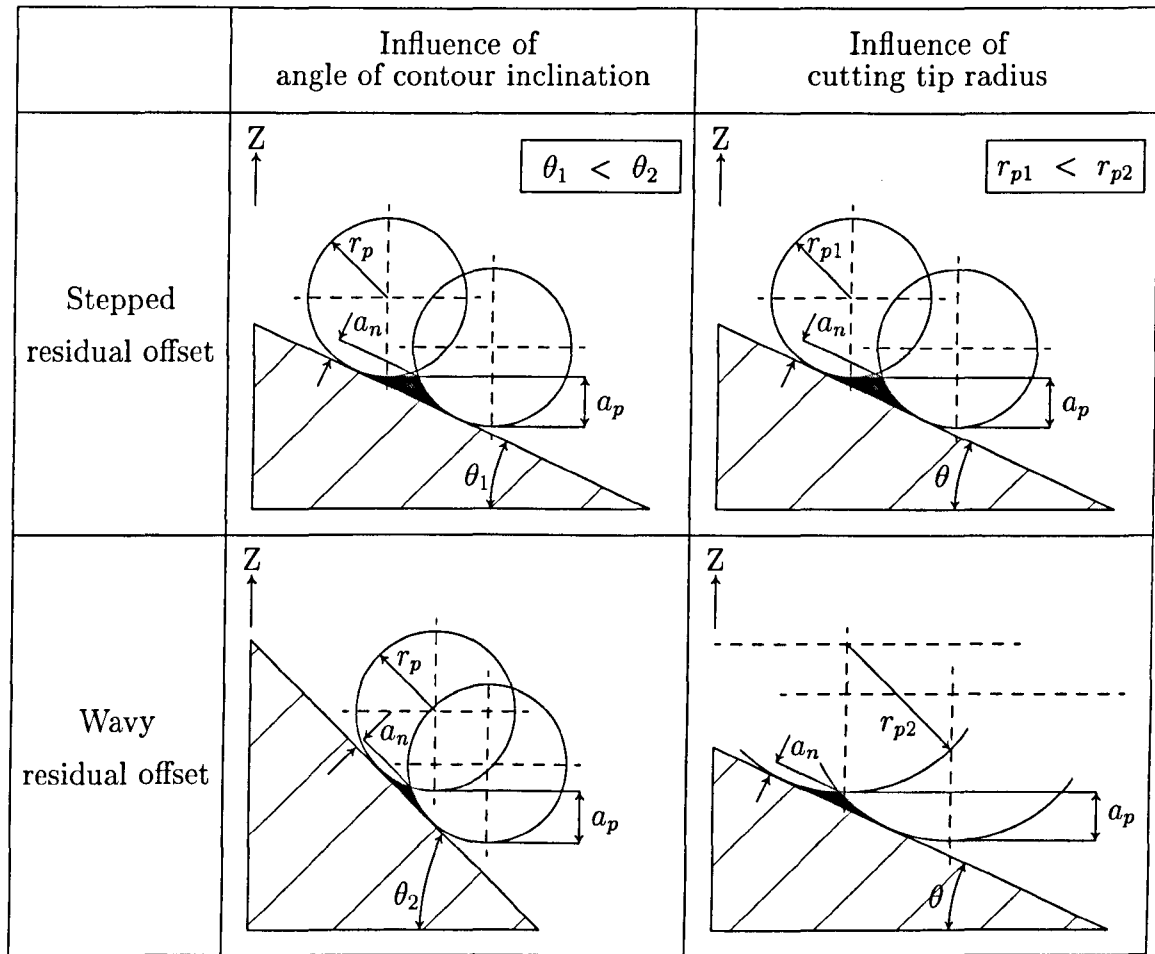
Figure 4.11: Residual offset situation

Due to the difference in surface formation, it is necessary to divide the mathematical description of the maximum normal offset a_n into two cases. A wavy surface structure exists when the point of the cut made by the cutter tip in the previous machining layer is located within an area of $90° > \kappa > 0°$ of the tip of the current machining layer.

In this case, the maximum perpendicular offset is:

$$a_{n_{max}} = r_p - \left((r_p - a_p) * \cos\theta + \sin\theta * \sqrt{r_p^2 * (r_p - a_p)^2} \right) \qquad (4.8)$$

In all other cases, a stepped offset exists. The following formula is used to calculate the maximum normal offset:

$$a_{n_{max}} = r_p - \sqrt{r_p^2 - \frac{a_p^2}{4 * \sin^2 \theta}}$$ (4.9)

Fig. 4.12 illustrates these relationships for a variation of the axial depth of cut and the radius of the cutter's carbide tip. Whereas a largely constant offset can be obtained in steep areas of the part, the formation of steps at shallow part inclination angles causes a sharp increase in the normal offset, which may assume values that nearly correspond to the adjusted axial depth of cut. From a geometric perspective, it is possible to counter this phenomenon by using a large cutter radius or reducing the axial depth of cut.
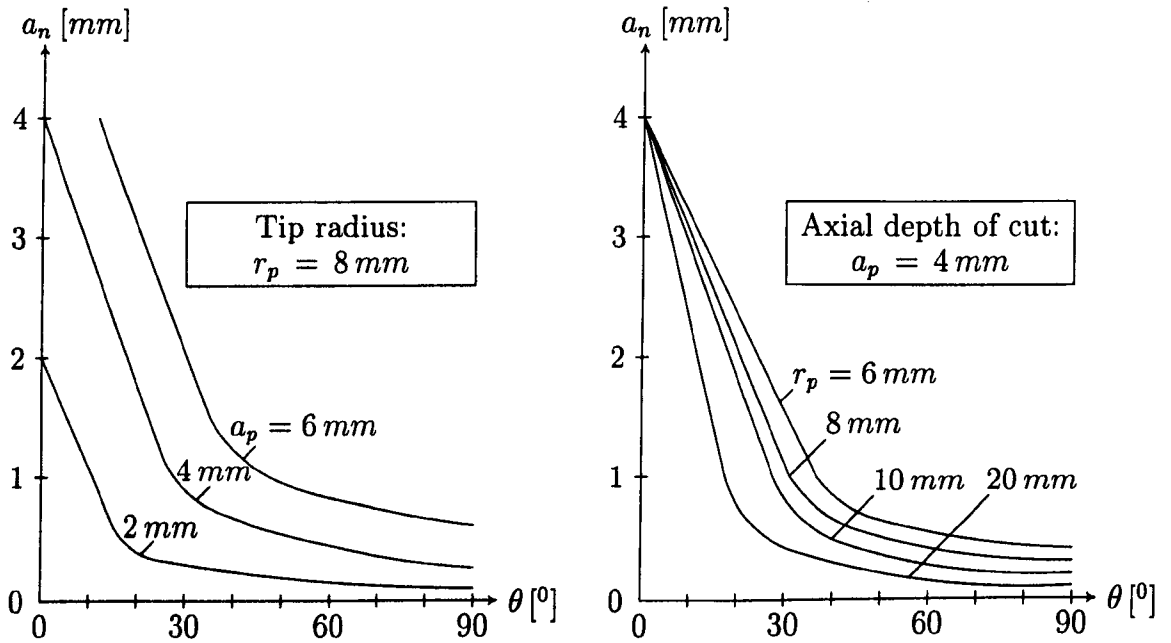
Figure 4.12: Factors influencing the normal offset

As the chart on the right in Fig. 4.12 shows, the normal offset decreases as the cutter radius increases. However, it can be influenced only insignificantly in level areas of the part. For these reasons, spherical ball-end mills produce only minimal geometric advantages with respect to the residual offset situation. In all cases, it is necessary to either reduce the axial depth of cut or re-machine the specific area of the part.

The illustrated geometric analysis clearly shows that a uniform offset situation can be achieved by adapting the axial depth of cut, regardless of the inclination of the contour. Although the radius of the carbide tip influences the maximum normal offset, a stepped residual offset always forms in level areas of the part. The maximum normal offset in such areas is determined primarily by the axial depth of cut that corresponds to the distance between the roughing layers. Therefore, to minimise residual offset, it makes sense to select a shallow axial depth of cut. The radius and diameter of the carbide tip can then be selected based on the criteria of process stability and rate of metal removal to ensure adequate process reliability and economy. But the geometric analysis illustrates that a large tip radius with adapted axial depth of cut should be a fundamental objective for roughing in layers.

4.5.2   Residual stock in the CAD/CAM system

When creating programmes for rough machining with commonly used CAD/CAM systems, the task of the NC programmer is complicated by the fact that the planner does not have detailed information about the current state of the blank following execution of an initial roughing programme. He cannot be certain which areas of the part have already been roughed down and which areas still require re-machining operations to remove residual stock. Only the geometry of the original blank and the setpoint geometry of the later part are available for creating the NC programme. The CAM system, and hence the user, have no information about the geometry of the current metal blank. To optimise cutter travel, e.g. retracts, and to obtain advantageous and uniform process parameters for HSC rough milling, the CAM system must have up-to-date information about the current state of the blank at all times. It is not sufficient to calculate a current blank following execution of the NC programme; information about the blank in every machined condition must be available. This requires dynamic updating of the blank, which the system must perform automatically. The virtual volume modelling of the stock removal process is the prerequisite for this.

If the CAM system is familiar with the current geometry of the metal blank at all times, it can make the updated blank available to the user in the form of CAD geometry following execution of an NC programme. By comparing the current blank with the later part, the system can display areas of remaining stock, e.g. steps or

pockets, to the user with the aid of convenient functions, e.g. shaded graphic views. The various depths of the material are displayed in different colours.

The user must remove this residual stock to obtain a clearly defined offset on the part. An additional roughing programme is calculated for this purpose, using the current blank. The user can then remove the remaining material with the aid of the roughing strategies described above. Machining of residual stock can be repeated as often as required because the blank can be continuously updated. Hence the user can be certain that the maximum offset on the pre-roughed blank conforms to the offset defined by the user.

Machining can then proceed to the finishing stage. The current blank should also be made available for the finishing process, completing the integrated process sequence from roughing to finishing.

4.6 Novel of contributions

Component quality, working speed and process monitoring are slogans in the die, mould and pattern manufacturing industry to optimize the premaching of parts. This chapter has analyzed all those components that influence the results of the roughing process; these have been combined and new standards set for the entire process. This has led to highly efficient roughing paths and optimum preparations for the finishing process.

Chapter 5

Clearing cutter fields

As described above, the basis for roughing in layers is the calculation of the boundaries of cutter fields in each of the layers to be machined. The boundaries of the cutter fields originate from positions at which the cutter has contact with a specified level and with the part or metal blank. All the closed boundaries of a layer result in topologically correct milling zones. The material situated within these zones must be completely removed in accordance with the requirements defined in Chapter 4. The algorithmic implementation of this task will be discussed in more detail in the following.

5.1 Distribution of milling paths

5.1.1 Isoparametric distribution of paths

The basis for isoparametric distribution of milling paths is the generation of a surface with the aid of the boundary contours of the cutter field. Two methods may be applied to generate the surface. The surface can be defined exactly by analytical expressions, or interpolation or approximation methods may be used. Suitable polynomial bases are applied for interpolation or approximation. Interpolation is an approximation principle which requires that the approximated surface coincide with the actual surface points at specified interpolation points. Methods established by Lagrange and Hermite and cubic splines are familiar surface-interpolation methods.

(

The task of approximation is to establish a numerically convenient approximation to a permanently defined surface. Familiar approximation methods include those from Coons and Bezier as well as the B-spline method.

A characteristic feature of parametric surface representation is that a value of the dependent variables is explicitly assigned to each value of the independent parameters u and v. This is not ensured in the case of explicit representation. In general, surfaces are not represented explicitly, but rather in the form of parameters. Thus the task of isoparametric path distribution is to generate parametrically uniformly distributed curves on the surface. A surface in a layer in parametric representation has the following form:

$$X = X(u, v)$$
$$Y = Y(u, v) \tag{5.1}$$

An essential factor here is that the coordinates X, Y are always derived through the parameters. An equation contingent on the degrees of freedom u and v, corresponding to an explicit representation, results for each coordinate X, Y. The lines produced where $u = const.$ and/or $v = const.$ are called isoparameters.

The two milling path layouts illustrated in Fig. 5.1 show an example of isoparametric path distribution. The contour of the metal blank consists of a rectangle, typical of a block-shaped blank. The contour of the part consists of a circle, which applies in the case of a cylindrical elevation in the part. With the aid of these two contours, a parametric surface was defined and its isoparameters generated.

If one considers the implementation of the individual target functions in the milling pattern on the left, it becomes evident that the target function climb milling is always optimally implemented. The overlap always satisfies the requirement of being greater than 0.5. With the aid of a rounding function, all paths are continuously tangent and the cutter is always in constant engagement because it never needs to leave the material and re-enter at some other location. This satisfies all four target requirements and reveals an optimum path distribution for clearing out cutter fields.
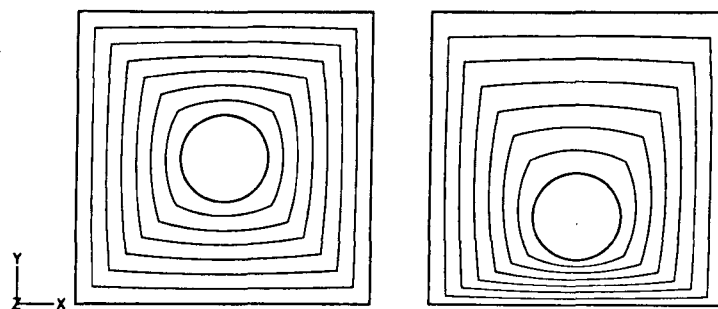
Figure 5.1: Isoparametric distribution of milling paths

However, as an examination of the milling pattern on the right in Fig. 5.1 clearly demonstrates, this statement applies only to certain geometric constellations of the cutter field.

The inability to define path spacing is the major drawback of this method. Paths tend to be denser in some areas, depending on the local situation. The cutting distance thus generated is much longer than would actually be necessary to remove stock from the cutter field. Even more serious, however, is the very small overlap, amounting to 0.0 in some cases. As a result, the cutter is no longer in constant engagement, which also reduces tool life. An overlap of 1.0 is achieved by enlarging path spacing and when machining on webs. The distance between paths may exceed the diameter of the cutter and stock will be left on the part. In the case of complex cutter fields, the effects of path density can become more and more critical and result in useless milling patterns.

5.1.2 Equidistant distribution of milling paths

Linear paths

Equidistant path distribution with linear paths is based on the generation of lines running parallel to a base line. In the CAD sector, this strategy for clearing cutter fields is referred to as paraxial milling. If the base line is parallel to the x or y drive axis of the milling machine, two of the machine's three linear drive axes can be clamped for milling. In the early stages of numerically controlled milling, the major advantage here was the minimum number of milling points, as only two milling points were required to instruct the machine to traverse a line. With the rapid development

of milling machines and their numeric control systems, this demand for a minimum number of milling points continues to diminish in significance and has no relevance whatsover for high-speed roughing.
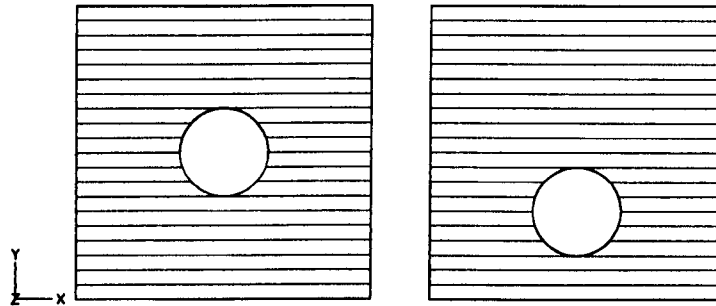

Figure 5.2: Paraxial path distribution

Fig. 5.2 demonstrates a paraxial path layout in which the paths were generated parallel to the x axis. A climb milling strategy can be implemented for this path layout only with the aid of numerous individual retract motions because the cutter must advance with idle motion over the entire part from the end of one milled path to the beginning of the next path. This method in no way satisfies the condition $F_{in} \gg F_{out}$. As Fig. 5.3 shows, the result is instead a traverse path in which the cutter travels more with idle motion than in contact with the material and thus $F_{out} > F_{in}$ applies. This extends cutter travel dramatically and thus prevents cost-effective machining. Due to strict adherence to the climb milling strategy, the cutter frequently strikes and leaves the workpiece. This reduces tool life. Moreover, this method results in very many tangentially discontinuous machine movements that, as described above, also tend to minimize tool life and exert an excessive load on the machine. Machining of the part contours represents a further disadvantage. When a paraxial milling path meets a part contour, the contour can first be completely traversed. This means that the cutter is in full engagement while traversing the contour, but cutter infeed from one path to another takes place in the open. Traversing the contour after machining the cutter field is another possibility. In this approach, the cutter is in full contact only when infeeding. If the contour is traversed at the end, the cutter will be constantly alternating between contact and idle travel. This is a highly adverse condition for tools used in high-speed roughing and can quickly result in breakage of the cutting edges. The sole advantage is contact with the stock within a cutter field while the cutter is engaged; this engagement is very uniform.
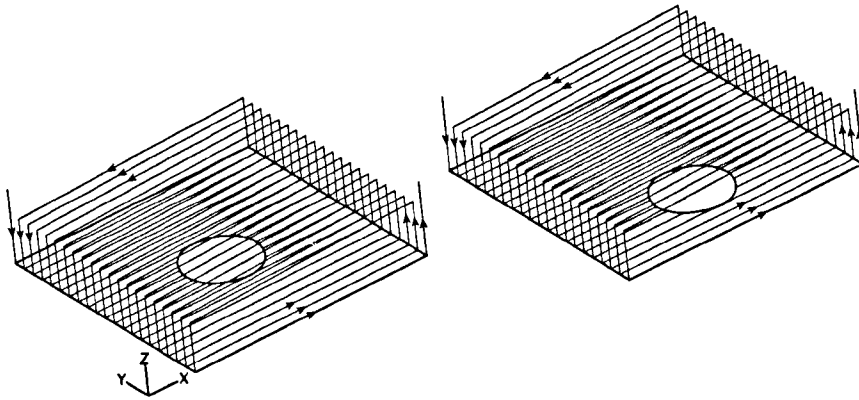
Figure 5.3: Milling programme with paraxial path distribution

This strategy can only be applied practically on milling machines with simple, out-dated machine kinematics linked to outdated CNC systems that are incapable of processing numerous NC positions, like those produced in curved milling paths, at sufficiently high speeds. Due to the heavy load they exert on machine kinematics, a result of their long life, the drive axes have a certain amount of play that best permits machining with a desired accuracy when two of the axes are clamped. Linear path distribution can also be applied for machining soft materials, where unconditional adherence to the target function of climb milling is irrelevant and very cost-effective roughing results can be obtained by means of reciprocal milling.

Due to the reasons mentioned above, it can be stated in summary that equidistant path distribution with the aid of linear paths is a highly unsatisfactory clearing strategy for high-speed roughing. In addition to factors that have a minimising effect on tool life, such as the cutter constantly striking and leaving the material, the excessive amount of idle travel rules out cost-effective machining.

Parallel milling paths

The basis for equidistant path distribution is the generation of curves or polygons parallel to a base curve. In the CAD/CAM sector, such curves are referred to as 'offset curves'. Since their introduction as control paths for numerically controlled machine tools, these curves have become the subject of increasing attention. In addition to their application in NC machining, offset curves have also been introduced into other areas such as road construction and laser cutting [12]. The geometry to be offset may

exist in the form of a curve or polygon. Processes used to generate offset geometries for polygons and curves have been dealt with extensively in relevant literature [9][12]. The parametric representation of an offset curve is shown below:

$$X_d(t) = X(t) + N(t)d \qquad (5.2)$$

where N is the standardised normal vector, i.e. $\mid N \mid = 1$. As illustrated in Fig. 5.4, d may be positive or negative when N is oriented accordingly; in this case, the associated offset curves are situated on different sides of the base curve [18].
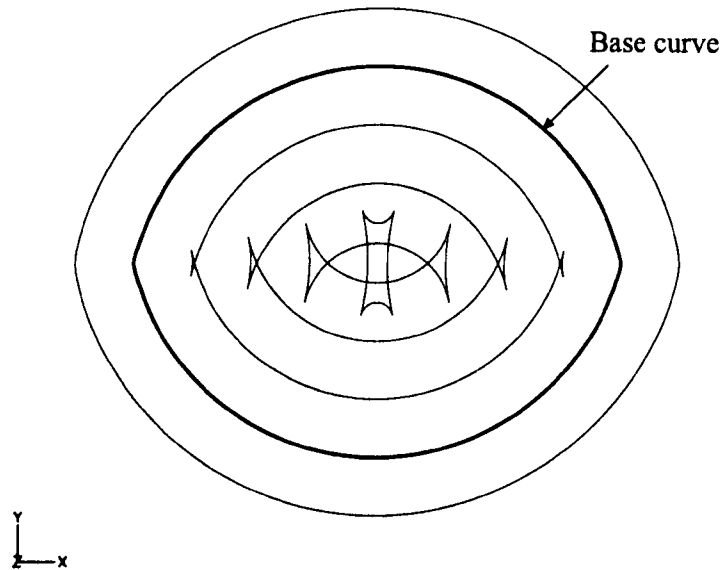
Figure 5.4: Offset curves of a plane curve

Farouki [12] describes a detailed representation of the differential-geometry properties of offset curves. If the base curve is not differentiable, the offset curve must be specially defined at such locations by supplementing it with circular segments. A further problem results when offset curves are checked for collision, i.e. when unwanted areas are eliminated. Hoschek [18] observed that prohibited areas always begin where offset curves penetrate each other (Fig. 5.5). This expands the scope of the collision check to the problem of detecting points of interpenetration. Thus the generation of offset curves entails the additional task of eliminating points of interpenetration.
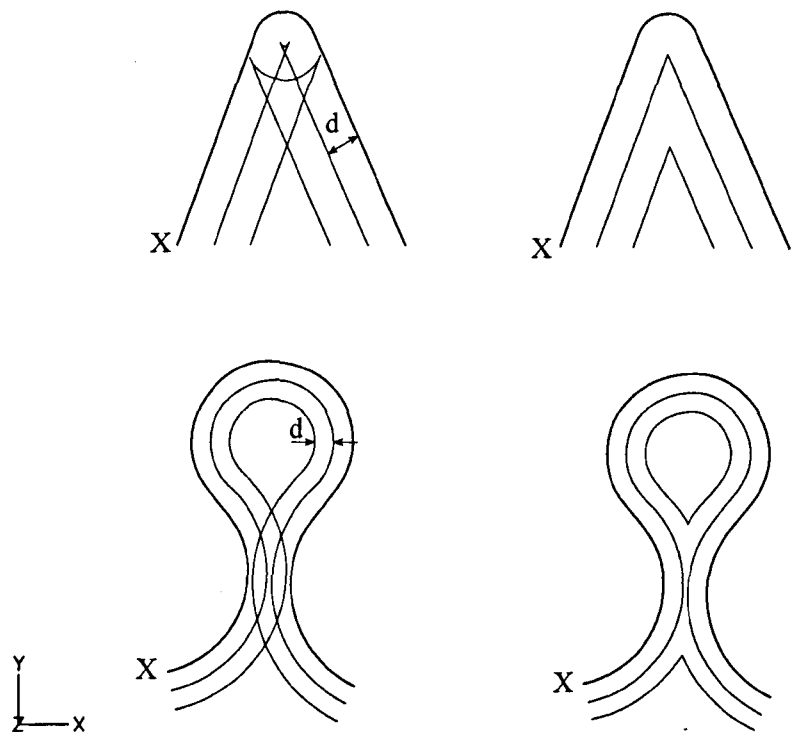
Figure 5.5: Collision of offset curves

If this is accomplished, milling path layouts like those shown at the right in Fig. 5.5 are generated. Due to the removal of the invalid curve segments, the offset curves split into individual areas, which will be referred to as nests in the following.

Fig. 5.6 illustrates a milling path layout created by calculating offset curves parallel to the outermost contour of the cutter field.
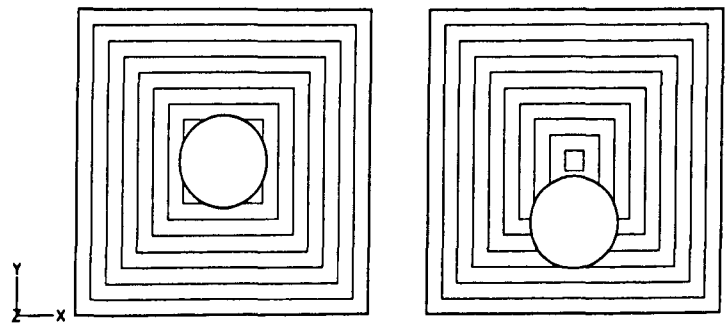
Figure 5.6: Path distribution with the aid of offset curves

It is obvious that the criteria for the specified target functions are almost completely satisfied. The target function climb milling $C_d(t) >= C_u(t)$ can be maintained unconditionally. The overlap $a_e(t)/D >= 0.5$ is maintained at all times with the exception of individual narrows. Tangentially continuous paths are also produced to a large extent. This requirement can also be satisfied on cusps and constrictions, where this target function is not realised, by simply rounding off the paths with a small radius. This method minimises cutter travel in idle movement F_{out}. The cutter must exit the material only when it traverses between nests. As described below, applying a suitable strategy can optimise this procedure. Thus, in comparison with the previously described isoparametric path distribution and equidistant path distribution using linear paths, this strategy proves to be the most technologically advantageous one for high-capacity roughing.

Closed contours that delimit the cutter field are a prerequisite for generating the field. At least one contour must exist. There may be more contours, e.g. three, as shown at the right in Fig. 5.8. The existence of one contour that encloses all of the others is a prerequisite. The former is referred to in the following as the outer contour. Contours situated within the outer contour are referred to in the following as inner contours. Inner contours may not enclose any further contours. Were this the case, the contours enclosed by the inner contours would, in turn, correspond to outer contours and would define a new cutter field. If the field has more than one contour, which is usually the case in roughing, it will be necessary to define a suitable base curve for generating the offset curves.

Base curve defined by an inner contour

In this method, the base curve is formed by all existing inner contours. If more than one inner contour exists, it will be connected to a contour by means of linear webs. The milling pattern at the right in Fig. 5.7 illustrates such a situation. The webs are arranged so that their length is minimal, i.e. the contours are connected at the points where they are closest to each other. If there is no inner contour, an auxiliary curve is generated automatically by the system within the milling zone. Starting from this base curve, offset curves are generated from the inside to the outside and the outer contour is clipped. The resulting curves or curve segments represent the milling paths to be traversed.

Upon evaluation of this milling path layout within the context of the technological requirements, it becomes obvious that the criterion climb milling can be achieved only by means of numerous idle movements. On all paths that intersect the outer contour and thus are not closed, the tool must either traverse the outer contour or withdraw to move to the next path. This in no way satisfies the criteria for the target function $\int^s F_{in}(s) >> \int^s F_{out}(s)$.
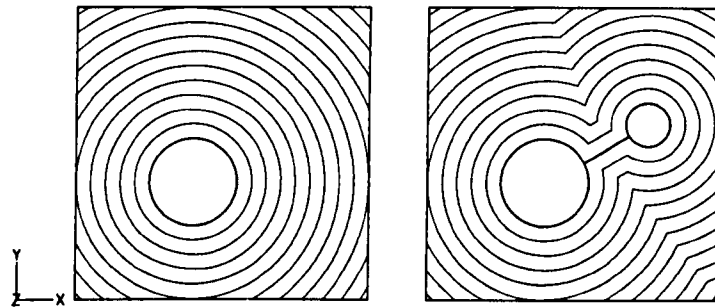
Figure 5.7: Base curve defined by inner contour

If a contour-parallel milling path intersects the outer contour, the question arises, as is the case with linear path distribution, as to whether the entire contour should be traversed immediately. If the contour is traversed at the end, the cutter will be constantly alternating between engagement and idle travel. This is a highly adverse condition for tools used in high-speed roughing and can quickly result in breakage of the cutting edges. The milling paths can be traversed either from the outside to the inside, or from the inside to the outside. If the paths are traversed from the inside to the outside, the base curve is traversed first. The cutter is in full contact and thus the proportion of conventional milling corresponds to the proportion of climb milling. As Fig. 4.10 clearly shows, tool life T diminishes sharply with an overlap of $a_e/D = 1$. For this reason, extended tool travel through solid material, as occurs particularly in the case of a base curve produced by webs, should be avoided. In the case of long base curves, this traversing strategy has a minimising effect on tool life. The only essential advantage here, in turn, is constant cutter engagement, to the extent that the tool is indeed in contact and there is no idle travel.

Base curve defined by an outer contour

In this method, the outer contour of the milling zone forms the base curve. Starting from this base curve, offset curves are generated from the outside to the inside and the inner contour is clipped. The resulting curves or curve segments represent the milling paths to be traversed by the tool. Fig. 5.8 shows an example of the resulting path layout.
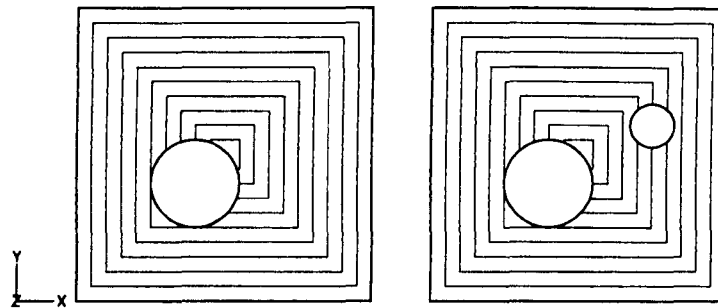
Figure 5.8: Base curve defined by outer contour

Upon evaluation of this milling path layout, one encounters the same disadvantages found when inner contours are offset. On all paths that intersect an inner contour and thus are not closed, the tool must either traverse the contour or withdraw to move to the next path. This in no way satisfies the criteria for the target function $\int^s F_{in}(s) \gg \int^s F_{out}(s)$. Here again, the problem arises of how to continue when an offset path meets an inner contour. Should the entire contour be traversed immediately, or after the cutter field has been completely machined? This question is extremely important with this method because, as a rule, inner contours are contours that were created by contact with the part. On such contours, the cutter traverses the part; the milling results are visible after roughing and are thus decisive for the roughing results. For this reason, such contours should always be traversed under optimum conditions, i.e. maintaining the selected overlap, using climb milling and, ideally, without interruption. Unfortunately, this cannot be achieved using an outer contour as a base curve. Due to the previously described drawbacks, this method does not deliver satisfactory path layouts either.

The awareness that, due to the non-observance of individual contours when offset curves are formed, the technological requirements placed on the clearing of a cutter field cannot be adequately satisfied is gained from the results obtained by developing

base curves from inner or outer contours. All contours, i.e. outer and inner contours, must be taken into account in the offsetting process. This basis will be elucidated in more detail below.

Base curve defined by contours

In this method the outer contour and all inner contours are connected by means of linear webs. The webs, in turn, are arranged in such a way that they are of minimum length, i.e. the contours are connected where they are closest to each other. This produces a single contour that serves as a base curve. The offset paths are generated from the outside toward the inside (Fig. 5.9).
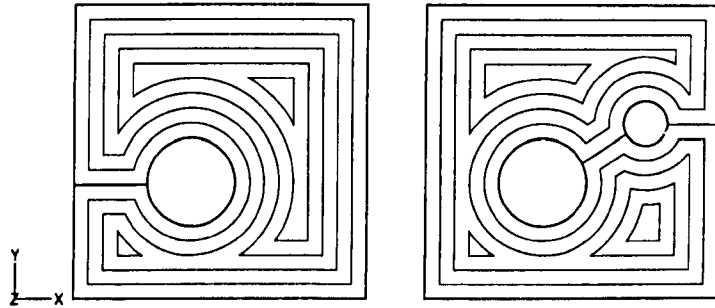
Figure 5.9: Base curve defined by contours

This method produces only closed paths and no open curve segments. No cutter withdrawal is required; the cutter must change in a suitable manner to a continuing milling path only where nests are formed. This fulfils the conditions of the target function $\int^s F_{in}(s) \gg \int^s F_{out}(s)$. The essential requirements, i.e. a climb milling strategy and an overlap of $a_e(t)/D >= 0.5$, but without remaining too long in engagement, can also be satisfied to a large extent. To a large extent and not entirely because the cutter traverses the base curve, i.e. the route along the webs and the inner contours, in full contact with the material and thus the familiar disadvantages become apparent. This strategy also tends toward excessive nest formation. Although this does not require extended idle travel because the cutter need not withdraw to a retract plane, it must leave the material and move at a local safety distance to the next valid path to re-enter the material. Despite these remaining drawbacks, all of the technological requirements can be nearly satisfied with a base curve through contours.

The disadvantages mentioned are compensated to a very large extent by the following strategy.

Dynamic base curve

In this method the base curve is adapted to the current local situation and thus changes dynamically. The outer contour serves as the first base curve. It is offset and examined for intersections with the inner contours. If there are no intersections, the offset curve serves as base curve and the offsetting procedure is repeated. If inner contours are intersected, a new base curve is generated in such a way that the inner contours are 'swallowed'. Offset curves are generated originating from the new base curve. Fig. 5.10 illustrates the procedure.
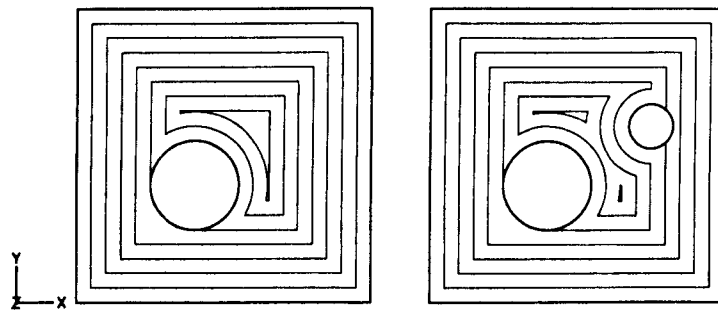
Figure 5.10: Dynamic base curve

Due to the assimilation of the inner contours, the swallowed sections are traversed in full contact with the material, while the sections of these contours that were not assimilated are not traversed. As previously described in the foregoing, however, these paths usually correspond to those contours of the part that must always be traversed completely under optimum conditions, i.e. maintaining the selected overlap, using a climb strategy and without interruption. To satisfy this requirement, a solution is selected in which the inner contours are not assimilated. Instead, they are offset toward the outside by the amount of the selected feed adjustment and intersected with the base curve, i.e. it is not the inner contours that are assimilated, but rather, their paths that have been offset by the amount of feed. Fig. 5.11 illustrates this method.

Upon examination of this milling path layout, it is apparent that the proportion
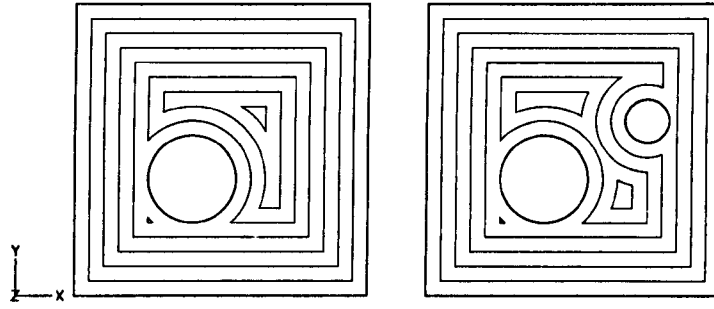
Figure 5.11: Dynamic base curve with complete inner contours

of conventional milling never predominates, i.e. the condition $C_d(t) \geq C_u(t)$ is satisfied. The requirement $a_e(t)/D \geq 0.5$ can be always be met with the exception of individual local narrowing. Cutter travel through solid material, i.e. $a_e(t)/D = 1$, occurs only on the assimilated contours. The cutter must never withdraw to maintain the climb strategy. Only where nests are formed must the cutter leave the material and move at a local safety distance to the next valid path to re-enter the material. However, because nest formation is minimised with this method, the criteria for the target function $\int^s F_{in}(s) \gg \int^s F_{out}(s)$ are also satisfied. By virtue of the principle that inner contours are never assimilated, they can always be traversed completely, without interruption, applying the climb strategy and, to a large extent, with the specified overlap. Based on these findings, equidistant path distribution using parallel paths is recommended for clearing out cutter fields in high-speed roughing operations. Thanks to a dynamic base curve, all existing contours are taken into account when paths are generated and the technological requirements placed on the clearing operation are satisfied to the largest possible extent.

5.2 Residual stock in cutter fields

The path layout for clearing a cutter field results from the contours of the field and the selected feed setting. When the cutter traverses these paths, care must be taken to ensure that the material situated within the field is completely cleared out. It was established in Chapter 4 that the feed setting or the radial contact width a_e should be at least as large as the cutter radius. This avoids impact loads on the tool's cutting edges and allows the tool to cut smoothly in the material.

As described above, the paths are generated with the aid of parallel paths or offset curves. If the selected feed adjustment or overlap satisfies the requirement $a_e(t)/D >= 0.5$, geometric constellations will exist in which material is not completely removed from a field. This is a result of the points of interpenetration of offset curves illustrated by the example in Fig. 5.5. Areas between points of interpenetration are removed when the path is generated. As illustrated in Fig. 5.12, three types of residual stock can be differentiated. The course of the offset curve is shown at the left of the figure. The dashed lines represent the areas between points of interpenetration, which are off-limits and thus cannot be traversed by the cutter. A top view of the surface areas traversed or overlapped by the cutter is shown at the right of Fig. 5.12. Areas not traversed by the cutter are shown in black color. Thus residual material remains in these areas of the cutter field. These areas of residue diminish as the overlap $a_e(t)/D$ approaches 0.5, and vanish completely with an overlap of 0.5. If the feed setting for machining is smaller than the cutter radius, these areas are not created, but the price paid for this advantage is a low rate of metal removal and shorter tool life. Application-oriented overlaps range from 0.6 and 0.8. For the NC programming system, this means that it must detect the generated areas of residual stock and eliminate them by means of a suitable strategy.
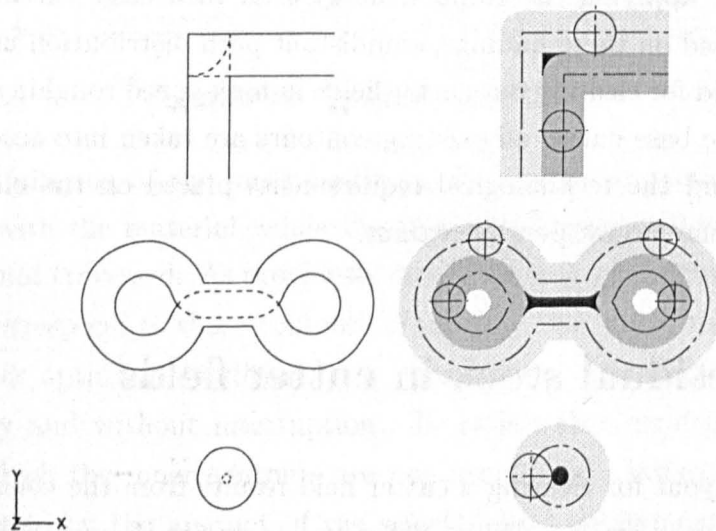
Figure 5.12: Residual stock in cutter fields

Areas of residual stock are detected using the technique illustrated at the right in Fig. 5.12. The surfaces created are those that the cutter passes over when it travels along

the outer and inner contours. These surfaces are joined and the face thus created is inspected for valid islands. If islands exist, they represent the areas of residual stock that were not removed by the cutter.

Three different strategies for removing this material are conceivable. The simplest method is to traverse all the milling paths of a cutter field and then analyse the area for remaining material. The material is then removed in a subsequent cut. However, this method conceals a few disadvantages. A cutter field may be very large in size. Numerous areas of residual stock may result and they may be situated far apart from each other. Thus the cutter must traverse long distances to reach such areas, necessitating a time-intensive milling programme. The tool travels with idle motion between the areas. To machine such areas, the cutter must constantly enter and leave the material. As discussed in Chapter 4, frequent entry and exit by the cutter is the primary cause of excessive tool wear and therefore must be avoided under all circumstances.

The second strategy is more intelligent and analyses the milling programme before it is executed. Cutter travel is inserted into the programme at locations where material remains. These appended milling paths may be linear or composed of a loop movement. This method is illustrated in Fig. 5.13.
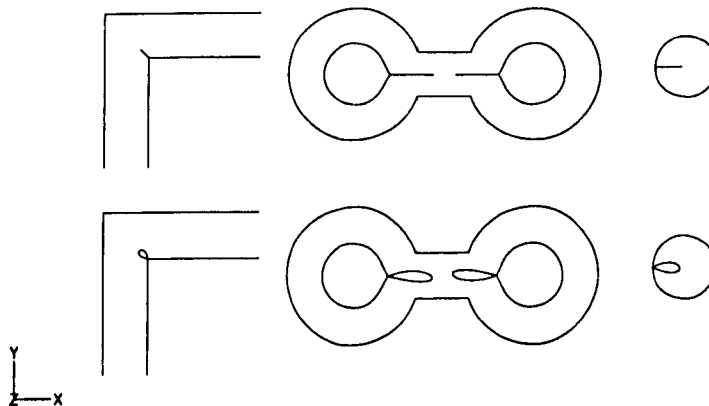
Figure 5.13: Tool travel to remove residual material

The advantage of this approach is the absence of the long idle tool travel that results with the first strategy. Only a single milling programme is required to remove the material; remachining is not necessary. If linear path segments are inserted, the cutter will feed vertically into the remaining material. This exerts a brief but very severe

shock load on the cutting edges. The cutter removes the material and then leaves along a linear path, returning with idle motion along the same path. The cutter then bites directly into the material again, which has a minimising effect on the life of the vulnerable cutting edges. Although the loop-motion concept eliminates these adverse technological conditions, it violates one essential criterion: Due to the loop, the material is cleared out using the conventional rather than the climb milling strategy. Conventional movements, however short, must be avoided under all circumstances because they represent an increased risk of breakage of the tool's cutting edges.

The best strategy is to ensure that no residual stock results at all. As established above, the areas of residual stock disappear as the feed setting decreases. With a feed setting identical to the cutter radius, no material remains in the cutter field. The formation of residual stock can be avoided entirely by allowing the NC programming system to reduce the adjusted feed rate locally. The procedure for this essentially corresponds to the one previously described: only the areas of residual stock are analysed upon generation of the milling paths. The outer path, or the base curve, is offset toward the inside by the amount of the feed setting. The area between the base curve and the offset curve(s) is examined for the presence of residual material. If such areas are detected, the offset value of the base curve is minimised at those locations to prevent the formation of residual stock. The offset value must be minimized to no less than the cutter radius to ensure that the criteria for the target function $a_e(t)/D >=$ 0.5 are always satisfied. Thus the base curve is not offset by the constant value of the feed setting but, instead, is assigned dynamic offset values that depend on local residual stock conditions. The resulting offset curves produce the milling path layout illustrated in Fig. 5.14, which complies with all the requirements placed on an HSC-oriented roughing process.
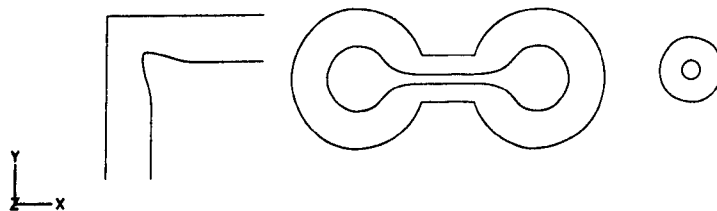
Figure 5.14: Offset curves with dynamic offset values

5.3 Rounding off milling paths

As stated in Chapter 4, cutter travel must be harmonious and should exhibit neither tangential discontinuity nor very small radii. Tangentially discontinuous paths, like those shown in Fig. 4.6, cause rapid tool wear. The cutter is briefly stationary at the lowest point, or when traversing the small radius, which causes the carbide tips to rub against the workpiece. Upon re-accelerating, the cutter bites into the solid material, exerting a very heavy shock load on the cutting edges. The brief stoppage of the machine subjects its kinematics to severe deceleration and acceleration forces. The machine control often handles small radii in the same way as tangential discontinuities and thus they result in the same technological drawbacks.

In addition to the heavy load exerted on the machine, a primary goal is to avoid influences that reduce cutter life by ensuring that the milling paths maintain a specified minimum curvature radius in all areas.

Contour-parallel milling paths are created using offset curve techniques. Tangentially discontinuous curve segments result where the offset curve exhibits points of interpenetration and the invalid areas are removed (Fig. 5.5). Small radii may be generated at any point on the offset curve. It is only necessary to offset a radius in the base curve toward the inside by a given amount. The curve at the upper left in Fig. 5.15 shows an example with tangential discontinuities and small radii. The curve does not have the required minimum curvature radius and, therefore, requires subsequent processing.

Consequently, the task is to modify curves in such a way that the smallest radius of curvature is greater than or equal to a specified value, i.e. kinks are rounded off and small radii eliminated. Two possible solutions were considered and will be elucidated in the following.

5.3.1 Rounding off by means of fourfold offsetting

The curve to be modified is offset by the amount of the desired radius in the normal direction and the invalid areas between intersections are removed. Reverse offsetting follows this procedure. In a further step, the same procedure is carried out opposite

to the normal direction of the curve. Fig. 5.15 demonstrates this fourfold offset procedure. Removing the invalid areas produces a resulting curve that complies with the specified requirements.
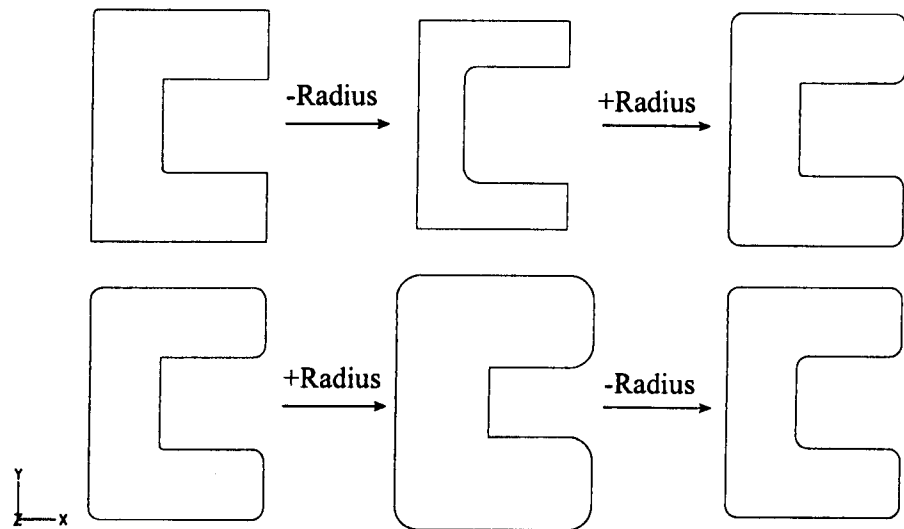
Figure 5.15: Rounding off by means of fourfold offsetting

But the disadvantage of this simple, global smoothing method is that it produces undesirable side effects. If one considers the curve at the upper left in Fig. 5.16, it becomes obvious that this curve is a valid curve in all areas, i.e. it exhibits the desired curvature radius throughout. However, the method applied causes it to be modified into two subcurves. The curve at the lower left in Fig. 5.16 shows an additional effect.
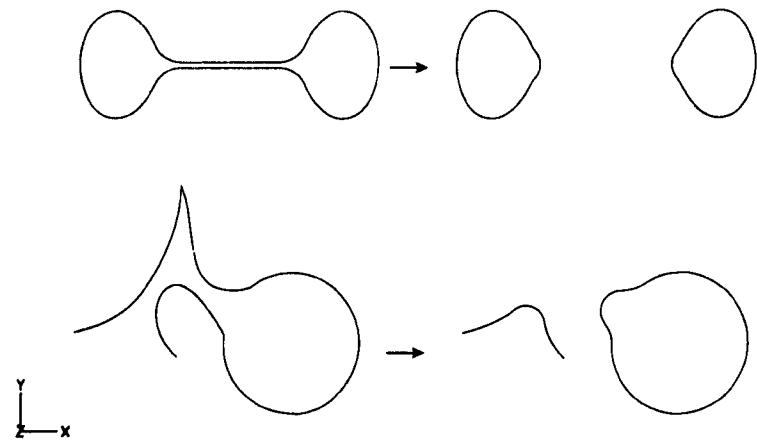
Figure 5.16: Decomposition of valid paths

Actually, this subarea of a curve to be modified fails to satisfy the requirement only at one point. But the method causes far greater modification to the curve than is necessary and thus its applicability must be called into question.

5.3.2 Rounding off by filtering

Tangential discontinuities and small radii in the milling path produce the negative consequences described in the foregoing. From another perspective, this may also be considered a lack of circularity of the milling paths. One way to generate the desired roundness is to smooth the milling paths. There are digital filters for this purpose that, for example, gradually increase the smoothness of the curves by cutting and inserting new points or by iterative application of operators that have a smoothing effect. Digital filters have been dealt with extensively in relevant literature. Fundamentals are adequately described in [5] and [6] and will not be discussed in further detail here.

The milling paths are generated with the aid of the offset technique described above. The paths exist in the form of curves. A simple filter, distinguished by its stability and computing speed, was developed for smoothing the curves. It will be described in the following.

To be able to smooth the curve, it is first made mathematically discrete and represented in a polygon. The task of the digital filter is to modify the points of the polygon with the aid of an operator. The new curve subsequently generated through the modified polygon points by approximation should exhibit the required smoothness and circularity.

The operator used by the filter is very simple. Input parameters are the point to be modified P_0, two predecessor points P_{-2}, P_{-1} and two successor points P_1, P_2. Due to the closed nature of the polygon, these entries are always possible. A cubic curve is interpolated through the two predecessor and successor points and the new value of the point P_0 is picked off at the centre of the cube. This results in a linear equation with fixed weights, with the aid of which point P_0 is modified. The modified point P_0' is supplied as the resulting point of the operator. The procedure is illustrated in Fig. 5.17.

The operator is applied to every point of the polygon. The five points of the operator
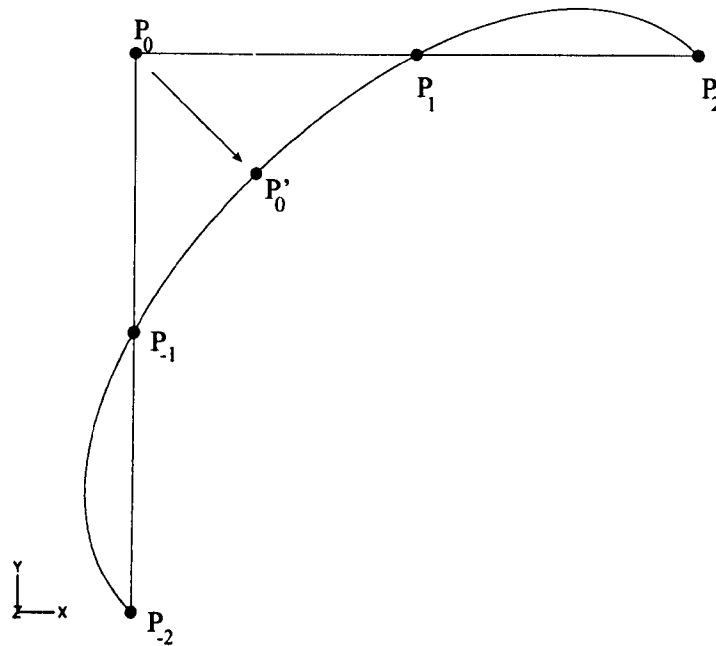
Figure 5.17: Operator

define a window, i.e. the filter in question is a real space filter. Real space filters are based on some form of moving window principle. A sample of data, in our case five points, is processed giving one output value. The window is then moved on to the next point and the process repeated.

To prevent fundamental changes in the contact conditions of the cutter when it traverses the curve, the resulting curve should deviate only within a certain tolerance from the original curve. This tolerance defines a tubular surface placed around the original curve. The modified curve should not leave the tube, i.e. it must lie entirely within the bounds of this three-dimensional tolerance band. As shown in Fig. 5.17, the modified point P_0' is situated at some distance from its original point P_0. To ensure adherence to the tube criterion, the point P_0' may not be situated outside the limits of the tube. If the modified point violates this criterion, it will be withdrawn into the tubular surface. This procedure is illustrated in Fig. 5.18.

If the discrete curve is captured as a digital signal, the high frequencies of the signal can be smoothed very rapidly using this simple filter. A single pass through all the discrete points of the curve is not sufficient to smooth low frequencies in the curve as well. Rather, the curve must be run through repeatedly in a loop until convergence of all
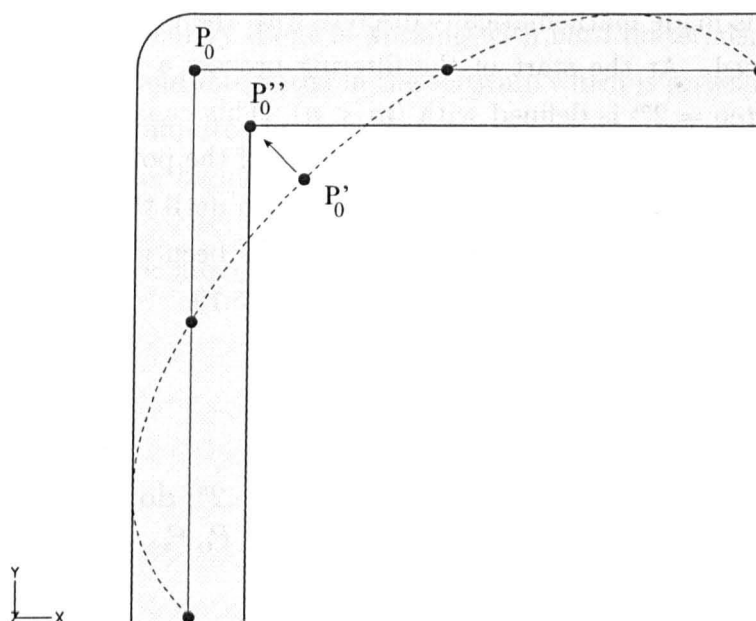
Figure 5.18: Tubular surface principle

the points is achieved. However, this has a negative impact on the time characteristics of the filter. A slight variation of the previously described method is used to achieve a more rapid convergence of the points, or fast smoothing of all frequencies. The window defined by the point to be modified and its two predecessor and successor points covers only a very limited local situation on the curve. This means that high frequencies of the curve lie within such a window while low frequencies are outside of it. If a larger window is selected, exactly the opposite situation occurs: the low frequencies are covered. The window can be enlarged by selecting a distinctly larger point grid instead of interpolating a cubic curve through the immediate predecessor and successor points of the point to be modified. For example, if the grid is selected with an interval of 16 points, the following point sequence results for the operator: P_{-32}, P_{-16}, P_0, P_{16}, P_{32}. This means that the first predecessor point P_{-32} is situated 32 points in front of the point to be modified P_0, the second predecessor point P_{-16} is situated 16 points in front of P_0, etc. This method can be used to enlarge or reduce the size of the viewed window as desired.

The property of large point grids to smooth low frequencies and of small point grids to smooth high frequencies can be exploited to achieve fast and reliable convergence of all the polygon points.

The curve is made mathematically discrete with the property that 2^n polygon points are generated. At the start of the filtering process a large point interval with the property $step = 2^m$ is defined with $(m < n)$. This causes every 2^mth polygon point to be modified during a first run. The spacing of the point grid is also 2^m. The point interval or the point grid is halved after each run until the point interval is one point, i.e. $step = 2^0$ and thus every polygon point has been modified. This simple scheme is illustrated in the form of pseudocode in Fig. 5.19.

```
step :=2ⁿ;
do:
    for i=0*step,1*step,2*step,...,2ⁿ; do:
        Operator(P_{i−step}, P_{i−step/2}, P_i, P_{i+step/2}, P_{i+step});
        SavePoint(P_i);
    step :=step/2;
while: step>=1
```

Figure 5.19: Pseudocode

This method rapidly smoothes low and high frequencies in the starting curve. Even withdrawing modified points situated outside the tubular surface does not impair the convergence characteristics nor the smoothness of the resulting curve. The complete mathematical theory, including all proof of convergence, is described in [1]. The resulting curves satisfy the specified requirements on curvature and, in their capacity as milling paths, meet the technological requirements on HSC-oriented roughing. Moreover, the algorithm is extremely robust and stable, very fast and does not result in any undesirable side effects. For these reasons, this method is preferable to the fourfold offset method for smoothing milling paths.

5.4 Novel of contributions

The ideal roughing strategy is to clear a cutter field optimize the tool life and reduce retract movements. The new technique, clears a cutter field by the use of a dynamic base curve with complete inner contours which fulfils these technological requirements to the largest possible extent. The strategy minimizes retract movements and helps to

optimize tool wear, particulary if one is working with hard materials. This technique is entirely implemented and integrated in the software which is presented in Appendix A. Also, the toolpaths computed by the software are rounded and smoothed automatically, so they are ideal for high feed rates. In addition, it recognizes the residual-path stock and automatically corrects the paths by inserting loop-shaped corner extensions. This is done by a new technique for creating offset curves with dynamic offset values.

Chapter 6

Updating the metal blank

An option for automatically updating the metal blank is an absolute prerequisite for an effective roughing module. Blank updating is defined as the mathematical generation of a description of the geometry produced by a milling process. Here, the starting point is always the geometric description of an original blank and an NC programme. The NC paths remove material from the part, generating a new geometry in the process. Obviously, it is precisely this true current geometry that the virtual world of the system must be familiar with to be able to effectively carry out subsequent steps in the machining process. The first question to be answered is the choice of a suitable modelling technique that will satisfy the requirements placed on the updating process. For this reason, various geometric modelling methods will be examined with respect to their suitability for updating blanks in the first part of this Chapter. A modelling method will then be selected that best meets the described requirements. The data structure of such a modeller will be described and a solution for the most difficult problem entailed in updating a blank-calculating the curves of intersection between volumes-will be presented.

6.1 Geometric modelling methods for CAD and CAM

CAD is only then truly effective for a roughing module if additional information can be derived from the computer model. Complete geometric information about three-dimensional objects is of primary interest when it comes to updating a blank and

regulating the feed setting. Such data cannot be derived from a simple line drawing. More sophisticated modelling methods are called for.

During the past few years, geometric modelling has evolved into an indispensable tool in modern design and manufacturing. Three different types of geometric modelling systems have been developed for practical applications: one based on curves, another based on surfaces and a third on solid bodies.

Simple CAD systems are based on two-dimensional wire frame models, which are used to represent projections of mechanical parts. Such systems are merely an electronic substitute for the drawing board, which offer the advantage of making it easier to edit and reproduce drawings. They also make for more flexible availability of preliminary designs via computer networks. Drawing objects consist mainly of straight linear segments and circular arcs as well as, in some cases, conics or splines. As is the case when drawn by hand, a drawing is produced by gradually joining various elements.

Although two-dimensional wire frame models are supposed to represent the projections of the edges of three-dimensional surfaces that envelope a physical solid, it is far too easy to generate meaningless models. These include, for example, shapes that cannot be assigned to any physical solid but, rather, remind one of an optical illusion, such as the object shown in Fig. 6.1.
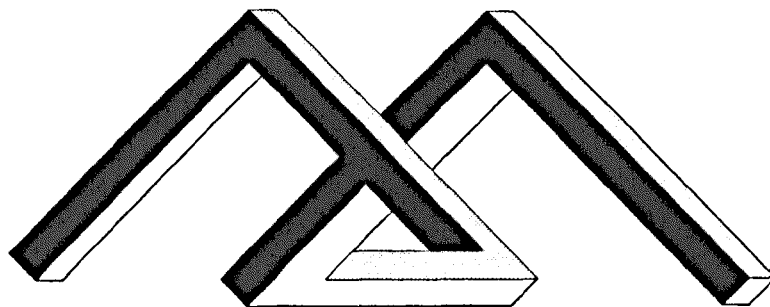
Figure 6.1: Wire frame model of a physical solid

Since two-dimensional wire frame models offer no option for computerised safeguarding of data integrity, a great deal of effort must be invested in error debugging. Although the situation is, of course, no worse than in the case of a model designed

on the drawing board, this modelling method is by no means adequate for obtaining complete information about 3D objects.

Three-dimensional wire frame models are only a partial remedy. Although an imitation like the one in Fig. 6.1 would no longer be possible because the projections of the three-dimensional wire frame model are machine-calculated, there are also three-dimensional wire frame models that cannot be associated with any physical body. For even if such a model is valid, it may still be ambiguous, as the ambiguity of the cube-like wire frame model shown in Fig. 6.2 demonstrates.
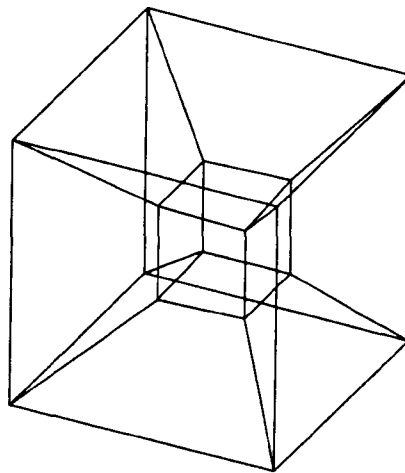
Figure 6.2: Ambiguous wire frame model

In practical applications, ambiguity is by far more dangerous than meaninglessness because the former usually cannot be detected at first glance. One criterion for exclusion is that the wire frame models lack information about the exact shape of a surface, unless all surfaces are fundamentally defined as plane surfaces. This is not sufficient for blanks and parts in die, mould and pattern manufacturing.

In summary, it can be stated that, although wire frame models are the simplest way to model geometric objects, the drawbacks are obvious: generation of a wire frame model is work-intensive, its design is prone to error, entirely meaningless, ambiguous and incomplete models can be created and, above all, it does not supply an adequate three-dimensional description of the object.

Methods for modelling with encompassing surfaces have been developed to overcome the difficulties presented by the wire frame model. There are mainly two different statements for surface modelling: curve interpolation and discrete approximation. In curve interpolation the surface is designed in such a way that it has a specified curve in three-dimensional space as a boundary curve. The boundary curves are constructed, taken from a wire frame model or derived by digitising. The goal is to construct surfaces with reasonable characteristics, i.e. neither too flat nor excessively curved. A widely used method, developed by Coons, interpolates a closed boundary curve defined by four edges. Extended, highly controllable surfaces can be modelled by combining several Coons' patches.

Approximating a curved surface by means of a control mesh of plane surfaces is referred to as discrete approximation. The most popular surface of this type is certainly the Bezier surface, developed in independent projects by Bezier at Renault and de Casteljau at Citroën. Like Coon's patches, Bezier patches can also be assembled into an extended surface. B-spline surfaces were developed to automatically check continuity when the patches are combined.

Surface models overcome many of the disadvantages of the wire frame model. For example, it is fundamentally impossible to produce a drawing such as the one shown in Fig. 6.1 using a surface model. Even the cubic solid becomes unambiguous once surfaces are introduced. Surface modelling remains the standard method for designing parts in die, mould and pattern manufacturing. But surface modelling also has disadvantages. As in the case of the wire frame model, constructing a complex surface assembled from numerous patches is a time-intensive and error-prone process. But the most serious problem arising with surface models, as with wire frame models, is their integrity. It is not automatically ensured that a surface (e.g. a self-intersecting one) limits a physical body in three-dimensional space. This prevents automatic computerised updating of the blank. These drawbacks were decisive for the analysis of more robust modelling techniques, solid modelling.

The aim of solid modelling is to supply the complete geometric information of real physical objects in three-dimensional space. Since this precisely satisfies the requirements for updating a blank and for dynamic feed regulation, this modelling method will now be examined in closer detail.

By definition, a solid is a three-dimensional body whose surface is such that an ant sitting upon it would view the surface at any given point as two-dimensional. One also refers to a two-dimensional, closed and orientable manifold. As is apparent in Fig. 6.3, the environment of a manifold does not differ essentially from its two-dimensional projection. This feature is exploited in the preparation of topologic maps, for example.
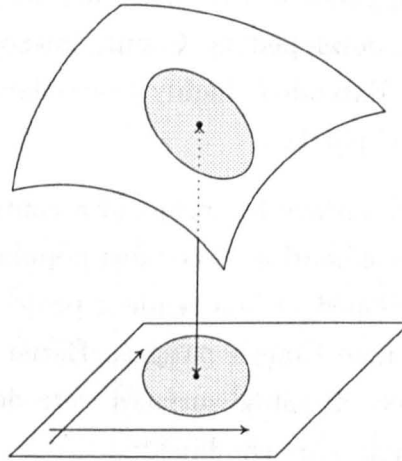
Figure 6.3: Two-dimensional manifold

A number of arrangements exist for storing computer models of solids. The most important of these are Constructive Solids Geometry (CSG) and Boundary Representations (BREP). Hybrid modellers are combinations of these two methods.

CSG assembles complex figures from simple geometric primitives. A diversity of figures can be generated by means of Boolean operations. Three operations are available: union, intersection and difference. Primitives are usually figures with relatively simple surfaces such as the cube, sphere, cylinder, torus and cone. As shown schematically in Fig. 6.4, a solid in the computer has structure similar to that of a binary tree, the nodes represent the operations and the leaves correspond to the primitives.

CSG representation has a number of strengths. First, it can be implemented quickly and easily. Second, every CSG tree represents a distinctly realisable physical body and, third, the tree reflects the manufacturing process of the body. For example, subtracting a cylinder corresponds to drilling a hole. The disadvantage of CSG representation is that the surface of the solid is not explicitly available. But knowledge of

the geometry and topology of the surface is necessary to permit the required properties of the solid to be determined. Limited or highly elaborate options for modelling complex geometries are a further drawback. Blanks and, above all, parts in die, mould and pattern manufacturing consist of complex geometries, a condition that permits only limited application of a CSG modeller. For these reasons, data structures have been developed to represent solids by means of their surfaces.

difference

union
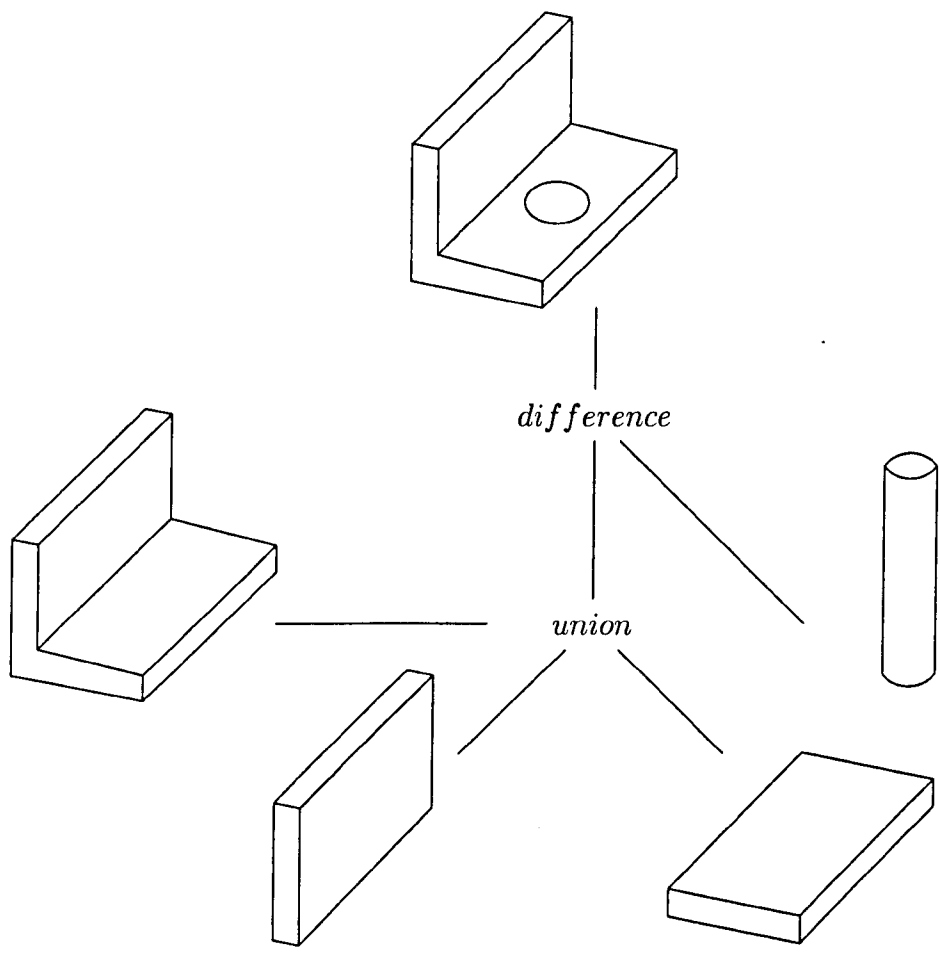
Figure 6.4: Constructive Solids Geometry structure

Boundary representation of a solid is more like a surface model. However, the topological structure of the surface is stored in addition to the complete geometric information. Topology is the 'science of rubber objects'. When a solid is deformed, topological properties are maintained as if it were made of rubber (cutting and pasting prohibited). For example, the number of holes in a pretzel remains constant,

no matter how it is deformed or how its surface is composed of patches. The most significant difference between a BREP and a common surface model, however, is the manner in which they are generated: In contrast to the surface model, which is composed of individual mutually independent patches, the patches in a BREP cannot be addressed individually. Rather, it is possible to create BREPs of union, intersection or difference from the BREPs of two solids. This ensures that the BREP indeed embodies a realisable physical body at all times. The advantages of the BREP for a roughing module are obvious: The explicit geometric and topological information of the surface make it possible at any time during a roughing operation to depict the current blank, adjust feed settings and optimise tool travel, e.g. retract motions, to correspond to the current geometry of the workpiece. The current blank is generated by simply subtracting a milled volume from the original blank. The disadvantage of this solution is the highly complex nature of a BREP modelling system.

In most solid modelling systems, these two formulations are combined in that the user works with the CSG representation while the BREP is executed internally in addition. This is referred to as a hybrid modeller. The benefit of the hybrid modeller is that the user need not assemble a surface model patch by patch; he or she can use previously modelled primitives to generate the surface models of solid bodies consistently by applying Boolean operations.

The efficiency of a solid modelling system depends heavily on which classes of surfaces it can model exactly. The simplest arrangement consists in working only with plane surfaces. This is referred to as a polyhedral solid modelling system. Since it can approximate any curved surfaces by means of sufficiently small pieces of the surface, there are practically no limits placed on the polyhedral solid modeller. However, actual practice demonstrates that, to achieve a very high degree of approximation accuracy, very large volumes of data must be generated and, consequently, very long computing times result. If additional classes of surfaces are introduced into a polyhedral solid modelling system, the increase in software-related complexity is determined primarily by the calculation of curves of intersection of random bounded pieces of the surface. These problems can be limited by introducing quadrics. These are second-order surfaces created by the motion of surfaces of revolution (spherical, cylindrical and conical surfaces, etc.). In turn, surfaces of revolution are generated by the revolution of sections such as circle, ellipse, parabola and hyperbola. The curves of section

of two quadrics can still be exactly calculated mathematically [26]. With surfaces capable of such exact modelling, areas of application emerge in which demand a degree of accuracy exceeding that provided by polyhedral solid modelling. Once quadrics are available, the next logical step is to add torus segments, which, for example, permit exact modelling of manifolds and conduits. However, the torus is already an algebraic surface of the fourth order and exact mathematical determination of curves of intersection with other surfaces is no longer possible. Although most parts can be modelled exactly using quadrics and tori, an option for working with free surfaces is preferred in die, mould and pattern manufacturing. The efficiency of such a modeller depends on its stability and performance when calculating the curves of intersections of free surfaces which, of course, can only be approximated.

6.2 Selection of a geometry modeller

For CAM-controlled production of a part in die, mould and pattern manufacturing, its geometric description must be available in the form of a CAD model that puts the part virtually in the hands of the user and allows him to view it from all sides. If the workpiece is to be machined by milling, the CAD system must also image the geometry of the metal blank. Thus updating of the blank cannot be considered as an isolated factor when selecting a suitable modelling system. On the contrary, the entire design process of geometries and all steps in manufacturing must be taken into account.

Part geometries in die, mould and pattern manufacturing do not consist merely of simple building blocks like cones, cylinders and cubes, but are composed of highly complex shapes that can only be described with sufficient accuracy by means of free-form geometry. An elaborate mathematical description is required for this type of object representation. To decrease complexity, the geometry is assembled from small patches that can be packed with relative ease in mathematical formulae. NURBS (Non Uniform Rational B-Spline) surfaces are employed for this purpose [7]. A single NURBS patch alone describes a complex, organically convex piece of a surface. Correspondingly few NURBS patches are required to describe an object. In contrast, if mathematically less complex surface pieces are selected for modelling, a correspondingly higher number of patches will be required. In general, one is confronted with

the option of selecting between a small quantity of complicated patches and a large quantity of simple patches. The simplest surface segments are the polygons, including the simplest of all: the triangle. There are a range of good reasons to construct part and blank geometries from triangles: one the one hand, nearly all graphics hardware is specialised in that area and, on the other, calculations for triangles are considerably more robust and easier to programme.

As described above, the milling of a part is divided into several individual steps. The machining sequence begins with roughing. In the roughing operation, an attempt is made to approximate the finished contour down to a minimum oversize, or offset, by cost-effective means. It is a matter of coarse, hence rough machining by which accuracy plays a secondary role. Positive deviations in the minimum offset of up to 0.1 mm can be tolerated by the subsequent machining procedure. Thus if the roughing operation were considered as an isolated case, a polyhedral representation of the blank and part surfaces would be fully adequate. Due to the limited accuracy required, the quantity of data needed to describe the geometries can be limited as well. By applying the progressive-mesh technique, local refinements can be made dynamically as required and thus data volumes minimised [7]. Due to the rapidly increasing processing power and memory capacity of today's computers, intensive computing operations can be performed within a very short time. Graphics options, such as shaded views, make for convenient display of the geometries.

However, finish machining calls for a considerably higher degree of accuracy. Only deviations within a range of 0.01 mm are tolerated. The number of triangles required for the task explodes in proportion to the increase in demands on the quality of the model. Whereas it is possible to roughly approximate a car door with a just few hundred triangles, for example, several thousand are required for a more detailed description. If even more importance is placed on the appearance of the finished surface, the number of triangles soon grows to a few hundred thousand. For this reason, a modern CAD/CAM system works with a free-surface modeller. The mathematical description of the free surfaces is then used as a basis for calculating NC finishing programmes.

Working with two different modelling systems in a CAD/CAM system for die, mould and pattern manufacturing would be a poor solution indeed: a polyhedral solid modeller for the geometry of the roughing process plus an exact solid modeller for the geom-

etry of the finishing operation. On the contrary, one will always have just one modeller in a CAD system that gives the user the means to generate geometries. Hardly anyone designs elaborate polygon models by hand with a modelling programme because effort increases exponentially with the degree of detail of the blank and part geometries. A more comfortable approach is via the free-surface modeller, which makes it possible to generate complex shapes conveniently. These free surfaces are combined topologically via a BREP into a totality or into a volume. Thus a solid modeller that permits convenient manipulation of free surfaces is chosen for modelling the geometry of blanks and parts.

The system calculates a new geometry when the blank is updated. This new geometry is determined by subtracting a milled volume from the original blank. To be able to subtract two volumes, the curves of intersection must first be defined. Defining the curves of intersection for a BREP with free surfaces is a highly complex and extremely computation-intensive task. As previously described, a representation of the geometry in a polyhedral solid modeller is sufficient for rough machining. This proposition, to work only with the triangle, the simplest of all polygons, promises an opportunity to implement simple, rapid and sound computational algorithms. This type of geometric representation particularly simplifies the task of defining the curves of intersection of two volumes.

Therefore, the software translates the individual free surfaces into an immense number of triangular facets, all of which are also interconnected topologically. All computations can be performed on the basis of these polyhedral solids. The process of updating the blank subtracts a polyhedral milling volume from the polyhedral original solid and generates a polyhedral geometry that corresponds to the current blank. The generated polyhedral solid should not be viewed isolated in a CAD system. Since the geometry and topology of a surface are to a large extent mutually independent, a modelling system based on complex free surfaces can use the same data structure used by a system that works exclusively with plane surfaces to store the topological data. It is logical to conclude that polyhedral solids are simple geometric entities of a free-surface modeller. If a polyhedral solid is not closed, it also has an edge that can easily be referenced to the edge of a free surface. Thus the polyhedral solid can be treated in the same way as a free surface and incorporated without difficulty into a BREP. At the same time, it provides an opportunity to use a 3D scanner to scan real

models and automatically generate polygon meshes from the data obtained. These meshes can be used for geometry description, edited and incorporated.

In summary it can be stated that a solid modeller that is capable of working with free surfaces should be chosen as a modelling method for a modern CAD/CAM system in die, mould and pattern manufacturing. The system must automatically generate polygon meshes as entities in order to make certain calculations and constructions fast, simple and robust-updating of blanks for rough machining or processing of digitised data, for example. Such meshes must be available in the form of normal geometric entities, and they must be capable of editing and of being integrated into the BREP. This modelling method satisfies all the requirements: fast, highly accurate and flexible design, on the one hand, and sound computations, on the other.

6.3   Topological data structure

Before an algorithm for calculating the curves of intersection of two polyhedral solids can be described, an effective topological data structure for such an entity must be selected. In contrast to the CSG modeller, a solid in boundary representation is defined indirectly by referencing the edges of its entities. In addition to geometric information such as surfaces, curves or, in the case of a triangular mesh, three-dimensional points, a boundary model must supply topological information about the relations that exist among the individual entities. Since, as described in the foregoing, the geometry and topology of a surface are independent of each other, a data structure is described that is valid both for a BREP consisting of free surfaces and a single mesh consisting of triangles.

The halfedge data structure for storing topological information is a component of the winged-edge data structure originally introduced by Baumgart in 1974 [26]. The connections among individual entities of the halfedge data structure are easier to grasp with the aid of the cuboid figure illustrated in Fig. 6.5 and the associated entities.

Face refers to a single bounded piece of the surface. A normal line whose direction is uniquely defined should be defined for each point on the face. All normal lines of the face point either into the solid or out of it. In a polygon mesh, a face corresponds to a triangle. The faces are connected along their edges. Each edge is bounded by

two vertices. The objects face, edge and vertex form the main entities of the halfedge
data structure.
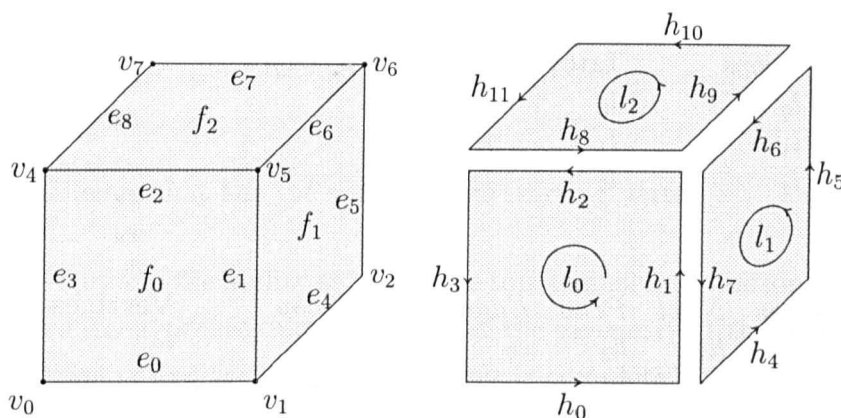
Figure 6.5: Topological halfedge model

A face may have any number of boundary curves, called loops. For example, the
surface of a sphere does not have a loop, whereas each of the end faces of a tube has
two loops, an inner and an outer one. An orientation is defined on the loops and can
be illustrated by means of the right-hand rule. For each point on the loop, the vector
product of the surface normal and one tangent vector on the loop that indicates the
orientation of the loop points toward the inside of the face.

Since, by definition, the surface of a solid is two-dimensional at every location (2D
manifold), no more than two faces may meet along each edge. If the surface of a
BREP is closed, at least two faces meet at each edge. Thus, all in all, exactly two
faces meet per edge in the case of a closed surface. A data structure for storing the
topological information of composite surfaces must make use of this property. To do
this, only those objects that satisfy the condition of consistency may be represented
in the structure. In the data structure, this is achieved by assigning halfedges to each
edge. Splitting edges into halfedges in this way makes it possible to view each loop as
a circular list of halfedges. The orientation of the loop is reflected in the sequence of
the circular list. Moreover, the consistent orientation of the loops and, consequently,
the halfedges, means that the two halfedges belonging to an edge always have an
opposite orientation. This can be seen on the edges e_1, e_2 and e_6 of the sample solid
shown in Fig. 6.5.

In summary, the following relevant data fields, as shown in Fig. 6.6, result for the entities face, edge, vertex, loop and halfedge:

Faces	Loops
f_0	l_0
f_1	l_1
f_2	l_2

Loops	Faces	Halfedges
l_0	f_0	h_0
l_1	f_1	h_4
l_2	f_2	h_8

Edges	Halfedges
e_0	h_0 −
e_1	h_1 h_7
e_2	h_2 h_8
....	....
e_7	h_{10} −
e_8	h_{11} −

Halfedges	Next	Prev	Edge	Vert	Loop
h_0	h_1	h_3	e_0	v_0	l_0
h_1	h_2	h_0	e_1	v_1	l_0
h_2	h_3	h_1	e_2	v_5	l_0
....	....	....	....	....	....
h_{10}	h_{11}	h_9	e_7	v_6	l_2
h_{11}	h_8	h_{10}	e_8	v_7	l_2

Vertices	Halfedges
v_0	h_0
v_1	h_1
v_2	h_5
....	....
v_6	h_{10}
v_7	h_{11}

Figure 6.6: Topological halfedge data structure

Face:

- Quantity of loops

Edge:

- The two associated halfedges

Loop:

- Face to which the loop belongs, any halfedge of the loop

Halfedge:

- Next halfedge in the loop

- Preceding halfedge in the loop

- Associated edge

- Associated loop

- Starting vertex of the halfedge

Vertex:

- Any halfedge that has the vertex as its starting vertex

The decisive factor is the ability to image the topological information of each surface in the halfedge data structure, independently of the geometry of the respective surfaces. The information stored in this data structure is complete in the sense that all cross-relationships among the objects are available and do not have to be searched for by means of a time-consuming database scan. For example, if an edge is known and one searches for the two adjacent faces, these can be found by going from the edge to the two associated halfedges and finally, by way of the associated loops, to the faces. There are any number of similar problem formulations. The completeness of the topological description permits accelerated calculations, e.g. the intersection of two solids. The representation of a solid is complete if the geometric information of the corresponding objects is stored in addition to the topological description. The result is the construction of a boundary representation.
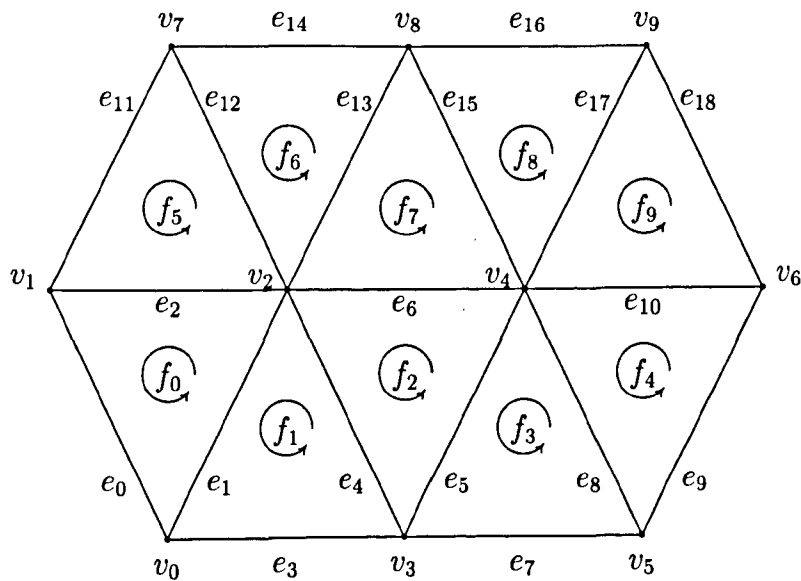
Figure 6.7: Topological model of a triangular mesh

The boundary representation introduced is a highly complex data structure. A property of a polyhedral solid, e.g. a triangular mesh, is that all edges are composed of linear segments. As illustrated in Fig. 6.7, this property makes it possible to simplify the topological data structure for this case.

The geometry can be defined completely by means of the coordinates of the vertices. Each edge knows its two vertices and faces. Each face knows its three edges and its three vertices. The listing of loops and halfedges becomes superfluous because the orientation of a face is reflected in the sequence of the three vertices of a face. Fig. 6.8 illustrates this simple topological data structure. The structure completely stores all topological and geometric information. Its contents subsequently supply the input for computations, e.g. an intersection of two triangular meshes.

Vertices	*Coordinates*	**Edges**	*Vertices*	*Faces*	**Faces**	*Vertices*	*Edges*
v_0	$x_0\ y_0\ z_0$	e_0	$v_0\ v_1$	$f_0 - 1$	f_0	$v_0\ v_2\ v_1$	$e_1\ e_2\ e_0$
v_1	$x_1\ y_0\ z_1$	e_1	$v_0\ v_1$	$f_0\ f_1$	f_1	$v_0\ v_3\ v_2$	$e_3\ e_4\ e_1$
v_2	$x_2\ y_0\ z_2$	e_2	$v_1\ v_2$	$f_0\ f_5$	f_2	$v_3\ v_4\ v_2$	$e_5\ e_6\ e_4$
v_3	$x_3\ y_0\ z_3$	e_3	$v_0\ v_3$	$f_1 - 1$	f_3	$v_3\ v_5\ v_4$	$e_7\ e_8\ e_5$
....		....			....		
v_8	$x_8\ y_0\ z_8$	e_{17}	$v_4\ v_9$	$f_8\ f_9$	f_8	$v_4\ v_9\ v_8$	$e_{17}\ e_{16}\ e_{15}$
v_9	$x_9\ y_0\ z_9$	e_{18}	$v_6\ v_9$	$f_9 - 1$	f_9	$v_4\ v_6\ v_9$	$e_{10}\ e_{18}\ e_{17}$

Figure 6.8: Data structure of a triangular mesh

6.4   Volume subtraction

The task of a roughing module is to update the geometry of the blank following each roughing operation. To do this, the milled volume must be subtracted from the original blank. This represents a Boolean operation. The actual difficulty encountered in calculating the Boolean operation lies in determining the separating curves of the components. To simplify this task somewhat, calculations for rough machining were limited to working with polyhedral solids. The simplest shape, the triangle, was selected for the entity of this solid, which consists only of plane surfaces. A second skin is mounted by means of triangulation beneath a solid that has been constructed using a complex free-surface modeller. This mesh is stored in the data format described

above. The mesh exhibits an accuracy with respect to exact surfaces that is adequate for roughing. The relatively wide tolerance results in meshes having a manageable dataset.

Upon closer examination of the volume subtraction illustrated in Fig. 6.9, it becomes evident that the calculation is divided into three areas:

- Determination of the curves of intersection

- Splitting of the solids at the curves of intersection

- Linking of the corresponding sub-solids
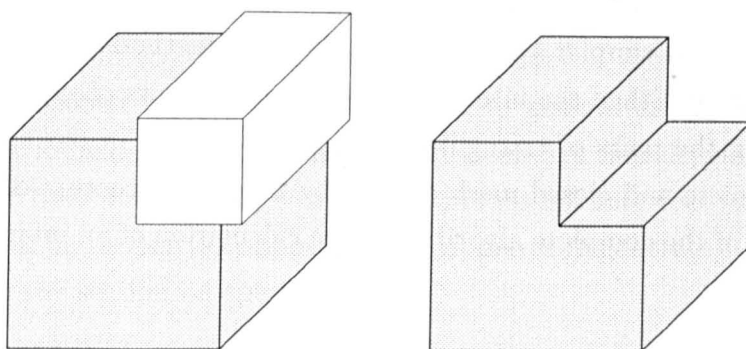
Figure 6.9: Volume subtraction

The goal is to furnish fast, stable and easy-to-implement rudimentary solutions to these three partial tasks. The topological data structure for a triangular mesh shown above always serves as a basis for this purpose. The selected basic solution for the most difficult subdomain, the calculation of curves of intersection, will be presented and discussed in detail below. Following calculation of the intersections, the subdomains splitting and linking the solids prove to be a simple derivative task because all the necessary topological information result from the intersection and are transported as information on the curves of intersection. For this reason, these purely logical solution rudiments will not be discussed in further detail. On the whole, the solution delivers very fast and stable algorithms that can be used to perform a volume subtraction of two polyhedral solids. This enables a roughing module to subtract the milled volume

from the original volume after each layer has been rough machined and supply the current updated geometry. Based on the current geometry, tool travel, e.g. retract and approach motions, can be optimised or minimised. This technique can be used to check tool-holding fixtures and the spindle head for collision with the workpiece, in addition to the tool itself.

6.5 Intersection of polyhedral solids

The intersection between solids appears in a wide range of applications. This problem arises in CAD/CAM applications where solids must be intersected. The problem also arises in other areas such as robotics where interference must be detected, and computer graphics where hidden surfaces are removed takes place. In almost all methods for intersection between solids, the surfaces of the solid are first subdivided into smaller and simpler surface pieces. In some methods, the smaller subpieces are triangulated and then the intersection between the pairs of surface pieces is found by intersecting the pairs of triangular surface pieces [29]. In our case, we have already got a complete and closed mesh defined by the data structure described above. The main part of the complete algorithm is the calculation of an intersection between two triangles.

The designer of an intersection algorithm has three goals at hand:

- The algorithm should be understandable, easy to encode and debug

- It should make optimal use of computer resources both with respect to storage space and execution time

- It has to be robust and has to deal with all special cases

6.5.1 Discussion of method

The methods used for intersecting a pair of triangles are based on the following three-step technique:

1. Create an unbounded plane containing one triangle

2. Intersect the second triangle with the plane of the first triangle. If an intersection exists, it is a bounded line segment. If an intersection segment is found, apply the step (1) above to the second triangle and step (2) to the first triangle to find another intersection segment.

3. If a second intersection segment exists, find a segment common to the two intersection segments. This common segment, if it exists, is then the required intersection of the two triangles.

Details of method

One approach to understanding the utility of Boolean intersection statements is to consider the tri-tri intersection in 3D space. Fig. 6.10 shows a view of two intersection triangles as a model for discussion. Each intersecting tri-tri pair will contribute one segment to the final intersection polygon. The vertices of the mesh are assumed to be generally positioned in R^3. This assumption of general as opposed to arbitrary positioned data indicates that the intersection is always non-degenerate. Triangles do not share vertices and the edges of tri-tri pairs do not intersect exactly. Thus, all intersections will be proper (as opposed to improper or degenerate). This restriction will be lifted in the section on special cases.
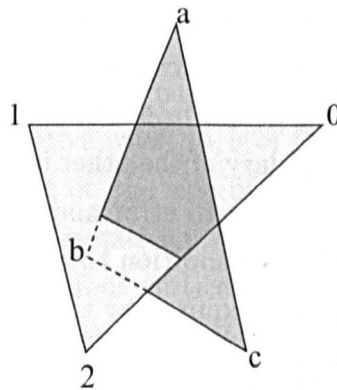

Figure 6.10: An intersecting pair of generally positioned triangles in three dimensions

Several approaches exist for computing such intersections, but a particularly attractive technique offers itself as a Boolean test. This method has the advantage that it can be performed robustly and quickly using only multiplication and addition, thus avoiding the inaccuracy and robustness pitfalls associated with division using fixed width representations of floating point numbers. It is useful to present a rather comprehensive treatment of this intersection primitive, not only to illustrate the development of the basic geometric computations, but also because the important topic of robustness, floating-point round-off-error and special cases will return to the expressions and assumptions exposed.

For two triangles to properly intersect in three-dimensional space, the following conditions must exist:

1. Two edges of one triangle must span the plane of the other.

2. If condition (1) exists, there must be a total of two edges (of six available), which penetrate the boundaries of the triangles (e.g. edge ab penetrates (012) and edge 02 penetrates (abc)).

Observations (1) and (2) reveal that the tri-tri intersection may be viewed a special arrangement of the more general problem of a segment-triangle intersection. This fundamental problem is common throughout the study of polygonal geometry. A variety of approaches to this basic problem exist. Generally the first approach that comes to mind is to directly compute the piercing points of the edges of one triangle into the plane of the other. Piercing points from one triangle's edges may then be tested for containment within the boundary of the other triangle. Unfortunately, this approach, while simple in concept, is prone to error and problematic when implemented using finite precision mathematics. In addition to demanding special effort to trap out zeros, the floating point division required by this approach may result in numbers that cannot be represented by finite width words, resulting in a loss of control over the accuracy of results and leading to serious problems with robustness.

An alternative to this slope-pierce test is to consider a Boolean check based on computation of a triple product without division. The attractive feature of a series of such logical checks is it permits one to establish the existence and connectivity of the segments without relying on the problematic computation of the actual piercing point

locations. The final step of computing the locations of these points may then be relegated to post-processing where they may be grouped together and, since connectivity is already established, floating point errors will not have fatal consequences.

The Boolean primitive for the 3D intersection of an edge and a triangle is based on the concept of the signed volume of a tetrahedron. This signed volume is based on the well-established relationship for the computation of the volume of a simplex, T, in n dimensions in determinate form. The signed volume $Vol(T)$ of the simplex T with vertices $(v_0, v_1, v_2, \ldots, v_n)$ in n dimensions is:

$$n!Vol(T_{v_0,v_1,\ldots,v_n}) = \begin{vmatrix} v_{0,0} & v_{0,1} & \cdots & v_{0,n-1} & 1 \\ & & \cdots\cdots\cdots\cdots\cdots\cdots & & \\ v_{n,0} & v_{n,1} & \cdots & v_{n,n-1} & 1 \end{vmatrix} \qquad (6.1)$$

where v_{ij} denotes the jth coordinate of the ith vertex with $j \in 0,1,2,\ldots,n-1$ and $i \in 0,1,2,\ldots,n$. In three dimensions, equation 6.1 gives six times the signed volume of the tetrahedron $T_{V_0 V_1 V_2 V_3}$.

$$6Vol(T_{v_0,v_1,v_2,v_3}) = \begin{vmatrix} v_{0,0} & v_{0,1} & v_{0,2} & 1 \\ v_{1,0} & v_{1,1} & v_{1,2} & 1 \\ v_{2,0} & v_{2,1} & v_{2,2} & 1 \\ v_{3,0} & v_{3,1} & v_{3,2} & 1 \end{vmatrix} \qquad (6.2)$$

This volume serves as the fundamental building block of the geometry engine used in intersect and cubes. It is positive when (a, b, c) forms an anticlockwise loop when viewed from an observation point on the side of the plane defined by (a, b, c) that is opposite the point d. Positive and negative volumes define the two states of a Boolean test, while zero indicates that the four vertices are exactly coplanar. If the vertices are indeed coplanar, then the situation constitutes a "tie", which will be resolved with a general tie-breaking algorithm (see section Special cases). In applying this logical test to edge ab and triangle $(0,1,2)$ in Fig. 6.10, ab spans the plane if and only if the signed volumes T_{012a} and T_{012b} have opposite signs. Fig. 6.11 presents a graphical look at the application of this test.

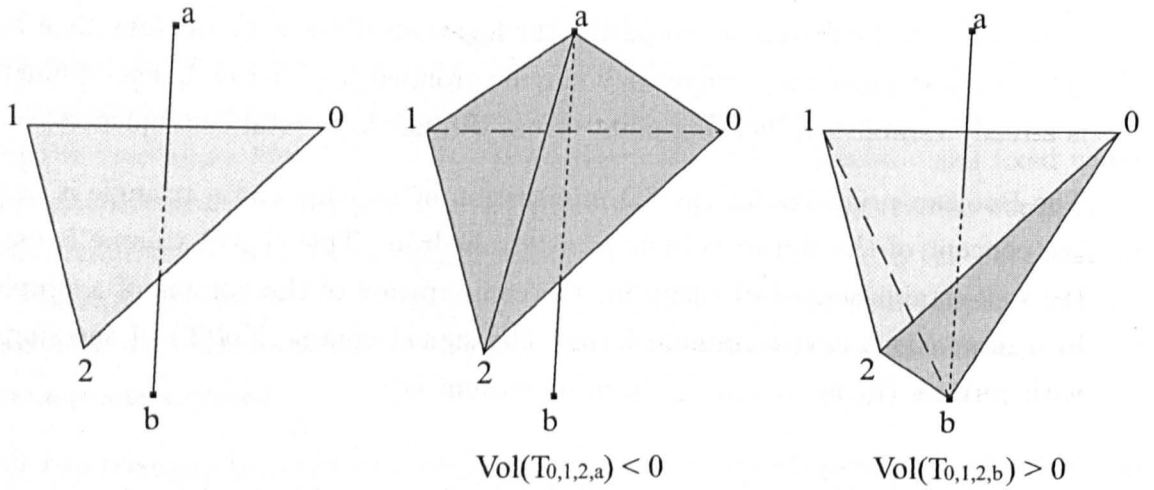$$\text{Vol}(T_{0,1,2,a}) < 0 \qquad\qquad \text{Vol}(T_{0,1,2,b}) > 0$$

Figure 6.11: Boolean test to check if edge ab spans the plane defined by triangle $(0, 1, 2)$

With a and b established as spanning the plane $(0, 1, 2)$ all that remains is to determine if ab pierces within the boundary of the triangle $(0, 1, 2)$. This will be the case if and only if the three tetrahedra formed by connecting the endpoints of ab with the three vertices of the triangle $(0, 1, 2)$ (taken two at a time) all have the same sign, that is

$$\Big(\big(Vol(T_{a,1,2,b}) < 0\big) \wedge \big(Vol(T_{a,0,1,b}) < 0\big) \wedge \big(Vol(T_{a,2,0,b}) < 0\big)\Big)$$

or

$$\Big(\big(Vol(T_{a,1,2,b}) > 0\big) \wedge \big(Vol(T_{a,0,1,b}) > 0\big) \wedge \big(Vol(T_{a,2,0,b}) > 0\big)\Big) \qquad (6.3)$$

Fig. 6.12 illustrates this test for the case where the three volumes are all positive.

After determining the existence of all the segments which result from the intersection between tri-tri pairs and connecting a linked list of all such segments to the triangles that intersect to produce them, all that remains is to actually compute the locations of the piercing points. This is accomplished by using a parametric representation of each intersected triangle and the edge, which penetrates it.

The signed volume computation of equation 6.2 is also used for performing inCircle/inSphere tests, for in/out determination in ray-casting algorithms and for a variety of other topological formulations. Due to its obvious importance, a great deal of research has gone into developing rapid and robust evaluations of this determinant.
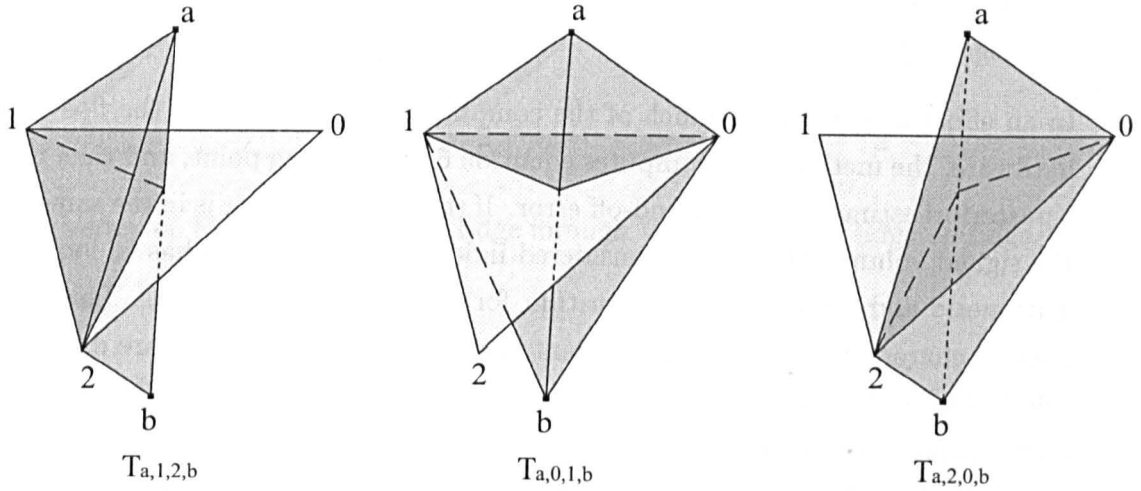

Figure 6.12: Boolean test for penetration of a line segment *ab* within the boundary of a triangle $(0, 1, 2)$

Computing the sign of equation 6.2 constitutes a topological primitive, which is an operation that tests an input and always yields one of a pre-specified number of results. Of course, such primitives can only classify, and new objects-like the actual locations of intersection points (see Fig. 6.10)-cannot be determined without further effort. Such topological primitives do, however, provide the intersections implicitly and this information is all that is really needed to establish the connectivity of the segment list describing the intersection.

The signed volume computation for arbitrarily positioned geometry can return a result, which is positive (return +1), negative (return -1) or zero (return 0), where +/-1 are non-degenerate cases and zero represents some geometric degeneracy. Distinguishing between these cases on finite precision hardware, however, is not necessarily a trivial task. Two approaches are common, the first may be thought of as an integer inflation strategy. In this approach all vertex locations are pre-processed so that the

data are inflated and adjusted to span the maximum allowable integer space, which can be represented by the hardware ($\pm(2^{31} - 1)$ with 32 bits or $\pm(2^{63} - 1)$ with 64 bits). New data are then constrained to the nearest permissible integer location. The second approach is to use exact (arbitrary precision) arithmetic. Unfortunately, while much hardware development has gone into rapid (round-off-prone) floating-point computation, few hardware architectures are optimised for either the arbitrary precision or integer math alternatives.

In an effort to perform as much of the computation as possible on the floating-point hardware, the method first computes equation 6.2 in floating point, and then makes an a posteriori estimate of the round-off error. If the round-off error is in the same order as the signed volume, the case is considered indeterminate and one has to look to exact arithmetic and introduce the algorithm for truly degenerate cases. This approach may be characterised as a floating-point filter, since only cases that are dangerous are selected for further processing. A brief discussion of this topic will follow below. Since only a small fraction of the computations fall through the filter, the speed penalty for using exact arithmetic on virtually all realistic examples is essentially negligible.

6.5.2 Special cases

Degeneracy arises in geometric data, as in the case of a tri-tri pair, due to the special position of two or more objects. Well-known examples in our case include co-planar, co-linear, or co-located vertices, and it is even possible for two edges to intersect exactly in three dimensions. Even more perplexing cases include those where two edges in special position overlap without sharing a vertex, or even having the decency to be co-linear. Fig. 6.13 shows three examples of such degeneracy. While seemingly unlikely (mathematically), degenerate data are common in the real world, and especially the somewhat quantised world of computational geometry. Since the overall utility of an implementation may depend upon the correct treatment of special cases, the handling of special cases can permeate the implementation.

Experience shows, that in geometric algorithms, much simpler than the intersection of two triangles, a very simple program is very often sufficient as long as one disregards all special cases. Only degenerate data cause trouble because one must find a special treatment for each speciality and take it into account in the program.
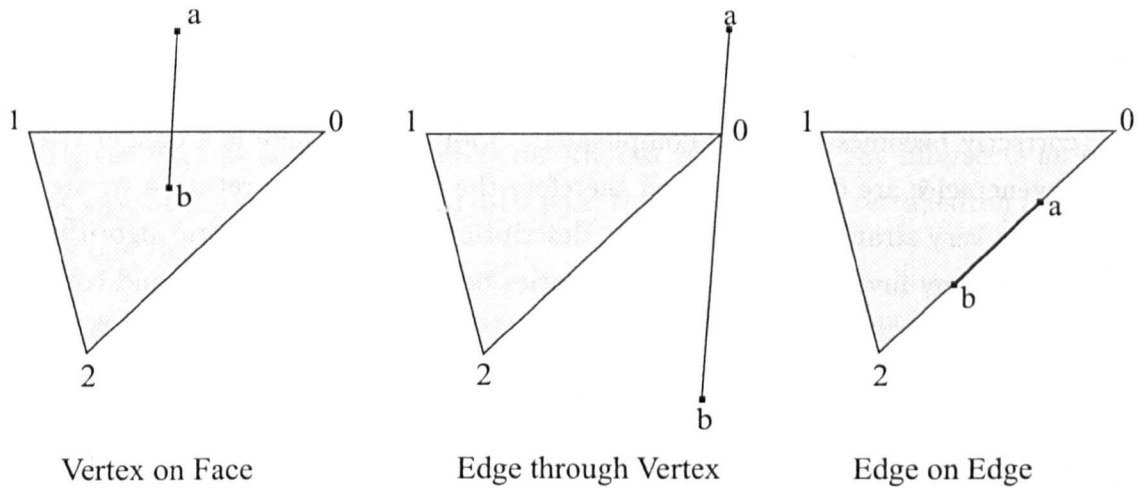
Vertex on Face   Edge through Vertex   Edge on Edge

Figure 6.13: Special cases

A very simple example may give an impression of the complications caused by re-
garding all special cases in a program for a geometric algorithm. The determination
of whether a point Q lies inside a polygon P is a standard algorithm of computer
graphics; see the left side of Fig. 6.14. As every intersection of an edge with a ray
R leading from Q to infinity indicates a change from inside to outside or vice-versa.
One need only count these intersections. Q lies inside P if the number is odd. The
simple program is shown at the right in Fig. 6.14.
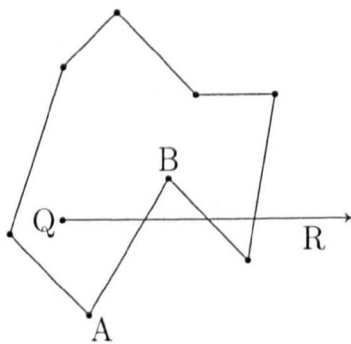

```
counter :=0;
for all edges do
    if ray intersects edge
        then ray increase counter;
inside :=odd(counter);
```

Figure 6.14: Points in polygon

A special case occurs when the ray R strikes a vertex of the polygon P; see Fig. 6.15. Then one must examine two or three consecutive edges simultaneously to decide whether one must count an intersection or not. A program treating all these cases correctly becomes long and complicated. Additionally, there is a danger that not all degeneracies are discovered, and therefore the program may return a wrong result in such a very strange case. Moreover, descriptions of many geometric algorithms do not contain any investigations on degeneracies because of their variety and complexity.
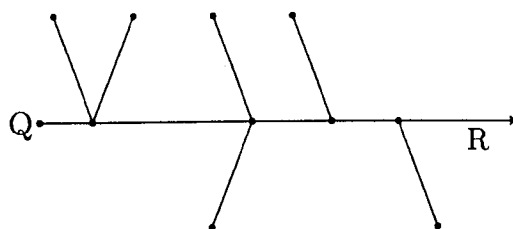
Figure 6.15: Special cases

How does a program find the correct decisions? When does it have to increase the counter in our simple example? It has to investigate whether an edge intersects the ray R. This is done by evaluating some expressions depending on the given data. For our example this is shown in Fig. 6.16.

ray intersects edge:

$$\boxed{y_Q - y_A} \qquad > 0$$

and

$$\boxed{y_Q - y_B} \qquad < 0$$

and

$$\boxed{distance\ of\ Q\ from\ A \to B} \quad < 0$$

or symmetric case with A as upper point

Figure 6.16: Topological primitives

The expression is built up from some functions, e.g. difference of two coordinate values or distance of a point from a directed straight line (negative if the point is in

the left half plane). Such functions are called topological primitives. The signs of the topological primitives are the means of controlling the algorithm. Fig. 6.16 shows that a combination of signs of the two primitives difference and distance evaluated with given data as actual parameters determines whether the ray intersects an edge. In the case of the intersection of a tri-tri pair, the volume of the tetrahedron (equation 6.2) is one topological primitive.

In any geometric algorithm there are some functions serving as topological primitives. In normal cases all evaluations with data values as actual parameters yield a positive or negative value. The result zero indicates a special case, in our example: two data values are equal or three points are collinear (a vertex lies on R or Q lies on an edge). In the case of the intersection of a tri-tri pair, the volume of the tetrahedron (equation 6.2) is equal to zero. This results, for example, if vertex a lies in the plane of triangle $(0, 1, 2)$.

Simulation of Simplicity

To deal with such degeneracies or ties, a tie-breaking algorithm is used. This tie-breaking algorithm stems from work done by Edelsbrunner and Mücke [10] and is known as Simulation of Simplicity (appropriately abbreviated as 'SOS'). The technique resolves geometric degeneracies by assuming a consistent set of virtual perturbations sufficient to insure that geometry is always in general position, in accordance with the assumptions outlined in the section 'Details of method'. The attraction of this approach is that the topological primitives never return a zero (degenerate) result, thus alleviating the need to consider specialized treatments for degenerate geometry. Moreover, since the perturbations are 'virtual' and 'consistent', data are never altered and ties are always resolved with the same result. Symbolic perturbation schemes like SOS are attractive for many reasons. Primarily, however, what is important is that they represent an algorithmic approach to tie-breaking. They do not depend on the experience of the programmer to foresee all possible diabolical cases, and virtually eliminate the need for special-case coding to trap out degeneracies arising from objects or data in special position.

The main idea of this method [10] is to perform the algorithm with perturbed data! Fig. 6.17 shows that after suitable changes the special case 'vertex lies on R ' does not

occur, i.e. no evaluation of the topological primitive 'difference' delivers zero, and the result 'inside' is the same for original and for perturbed data. In the same manner, the topological primitive 'Volume of a tetrahedron' (equation 6.2) also never returns a zero and therefore we are always able to calculate the intersection of a tri-tri pair.
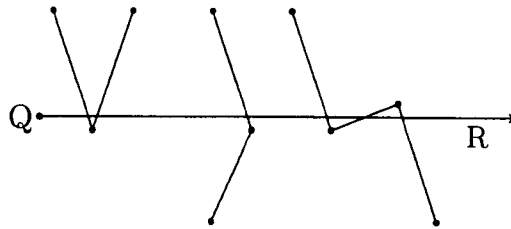
Figure 6.17: No special case after perturbation

The perturbations have to fulfil some conditions:

- They have to be so small that neither a new special case arises (e.g. a vertex moves onto R) nor does the topology change (e.g. a vertex moves to the other side of R).

- The perturbations of different data have to be different in order to remove all special relative positions of different objects (e.g. all vertices have different heights after perturbation).

Edlesbrunner and Mücke have proved that the following method works correctly for our problem of solving equation 6.2. The vertices are $V = \{v_0, v_1, v_2, v_3\}$ where v_{ij} denotes the jth coordinate of the ith vertex with $j \in \{0, 1, 2\}$ and $i \in \{0, 1, 2, 3\}$. Every vertex is definitively connected with its perturbation index i defining the size of its perturbation. It is important that each vertex have a unique index. The perturbation is realised by replacing each vertex by a polynomial in ε. The perturbations are defined by

$$\varepsilon(i,j) = \varepsilon^{2^{3i-j}} \tag{6.4}$$

where ε is a small positive number. It is not necessary to calculate its numerical value for performing the algorithm with perturbed data. Instead one has to imagine that

it is so small that the conditions mentioned above hold. Now the perturbed vertices are:

$$v^*_{i,j} = v_{i,j} + \varepsilon_{i,j} \tag{6.5}$$

and equation 6.2:

$$6Vol^*(T_{v_0,v_1,v_2,v_3}) = \begin{vmatrix} v_{0,0} + \varepsilon_{0,0} & v_{0,1} + \varepsilon_{0,1} & v_{0,2} + \varepsilon_{0,2} & 1 \\ v_{1,0} + \varepsilon_{1,0} & v_{1,1} + \varepsilon_{1,1} & v_{1,2} + \varepsilon_{1,2} & 1 \\ v_{2,0} + \varepsilon_{2,0} & v_{2,1} + \varepsilon_{2,1} & v_{2,2} + \varepsilon_{2,2} & 1 \\ v_{3,0} + \varepsilon_{3,0} & v_{3,1} + \varepsilon_{3,1} & v_{3,2} + \varepsilon_{3,2} & 1 \end{vmatrix} \tag{6.6}$$

Now the following theorem holds:

Theorem: All calls of equation 6.2 with perturbed data as actual parameters deliver a result different from zero and therefore special cases do not occur:

$$6Vol(T_{v_0v_1v_2v_3}) \neq 0 \tag{6.7}$$

The proof of this theorem is based on the fact that all terms occurring when expanding the determinant (with perturbed data replacing the v_i) have different ε-exponents because of the subtle choice of exponents in 6.4. Therefore the term with lowest ε-exponent (all terms have the form: *constant multiplier* $* \ \varepsilon^{exponent}$) that is different from zero is value-dominant, i.e. for small ε it cannot be compensated by others and therefore defines the sign of 6.7.

Now the calculation of the volume of the tetrahedron (equation 6.2) always terminates with result different from zero. This rule for calculating the sign of this topological primitive enables us to perform the algorithm for perturbed data. The simple program, disregarding all special cases, delivers the correct result every time because the result is the same as for original data, and special cases do not occur. The only prerequisite is that the data be accessed only via topological primitives programmed as shown above.

For the reliable decision whether the result is zero it is not always necessary to use time consuming exact arithmetic. As only the sign of the result is required (not its value) we can speed up the calculation substantially: First calculate with floating

point arithmetic and then estimate the possible round-off error. If the round-off error is not of the same order as the signed volume then we know the correct sign. Only if the answer is ambiguous, do we have to use exact computation. In most cases we can finish after calculating $6Vol(T_{V_0V_1V_2V_3})$ with floating point arithmetic because the topological primitive is a very simple function and the result gives the final answer in all cases clearly distinct from zero.

6.6 Novel of contributions

Virtual production tracking is the way of knowing what is really going to happen in the real machining world. The software module, designed by the author, for roughing in layers integrates this functionality so that it can take the residual stock model into account as it computes an NC program. Minimized idle tool travel is the result. The software updates blank geometries on the fly. This is done by the technique described above. Toolpath calculations take into account the way in which the geometry of the component emerges as the selected milling cutter removes stock layer by layer. This means that the software always knows the residual stock remaining on the component and can reduce infeed and positioning movements to the optimized minimum.

The intermediate geometry computed is used as the new geometry of the blank. This selective remachining has several advantages:

- It uses a smaller cutter to clear out even the smallest recesses.

- It uses tighter spacing between layers to remove cusps.

- It uses a different tool orientation to cope with steep slopes and undercut areas.

The total machining time is minimized because the blank geometry was freshly updated beforehand and only the areas of residual stock are milled. Retract and infeed movements are also reduced to a minimum when the blank geometry is updated on the fly. These processes are unique in the CAD/CAM market.

Chapter 7

Summary and Outlook

During the past few years, a trend toward shorter product cycles for many commodities can be observed. This phenomenon has had an impact on the manufacturing of complex workpieces. These changes in the market, together with a simultaneous demand for improved quality at lower cost are particularly noticeable in die, mould and pattern manufacturing. They are forcing companies to increase efficiency in the design, planning and production of workpieces.

Due to advancements made in the sector of CAD technology, many companies are now in a position to design workpieces in less time. CAM systems with integrated NC programming systems have brought about a considerable increase in efficiency in manufacturing these workpieces as well. Moreover, there has been a trend in recent years toward the application of high-speed cutting for finish machining in die, mould and pattern manufacturing. Closer steps, shorter machining times and improved workpiece quality have already resulted in great potential for rationalisation in this area. However, the transition from roughing to finishing still poses problems. Here is a gap in the process sequence that may also be described as the transition from a staircase structure to a uniform offset.

In addition to satisfying technical machine- and control-related conditions, the use of highly wear-resistant tools and, above all, suitable milling strategies is of decisive importance for the successful application of HSC. In particular, technological process parameters must be taken into account in the layout of such cutting strategies. Until now, these parameters of machining technology have been only inadequately acknowl-

edged in NC programming systems. Often only the geometric representation of the part is considered as the sole reference for calculating NC tool travel. This applies to the calculation of both HSC finishing and roughing programmes. Upon closer examination of HSC process parameters, it becomes obvious that they are also valid for roughing in layers. When they are also taken into account in rough machining applications, the result is an enormous increase in efficiency for pre-machining parts.

The aim of rough machining has been to achieve maximum stock-removal capacities while conserving the milling machine, cutter and cutting material. However, due to the application of HSC, this aim is shifting in favour of a constant offset following the roughing operation accompanied by the elimination of time-consuming pre-finishing operations.

This stated aim of this endeavour is to compile the technological milling requirements for rough machining based on the process expertise gained from HSC and establish them in a CAD/CAM concept. The technological aspects have been taken into account and implemented in the development of new software.

In addition to geometric tool data, the CAD/CAM system must take technological properties, e.g. cutting materials and plunge capabilities, into account when milling cutters are selected. This is necessary above all when viewed against the background of an adjusted feed setting, dependent on the current local conditions of tool engagement. The virtual system must have complete and precise information about the geometric data, the part and the metal blank.

The process-related technological requirements for clearing out cutter fields are characterised by the demand for extended cutter service life. This is achieved by using the climb milling strategy, harmonious contour characteristics, circular entry and exit cuts and a shallow cutter entry plunge into the stock. However, an essential factor is the avoidance of entry and exit cuts; the cutter should be in continuous engagement. To prevent heavy shock loads on the tool's cutting edges and obtain a smooth cut into the material, the radial contact by the cutter should always be larger than its radius. To minimise idle tool travel, the current blank must be known at all times. This calls for dynamic updating of the blank geometry. Following an initial roughing operation, the blank features the typical stepped or wavy residual offset. The CAD/CAM system must be familiar with this geometry. It is precisely this residual stock that must be

removed by the subsequent machining operation to maintain a constant offset on the part and permit immediate transition to the finishing operation. The current blank is passed on to the finishing process, closing the process sequence between roughing and finishing.

There were two major work areas for implementing software for this requirement: the clearing of cutter fields and the updating of the metal blank.

Isoparametric and equidistant path distribution was discussed as a solution for clearing out cutter fields. Equidistant path distribution with the aid of parallel paths to base or offset curves was judged to be the technologically most advantageous method. Several options for selecting base curves were elucidated and, with the dynamic base curve, a solution was found in which no tool withdrawal movements are required, conventional milling never predominates and no extended tool travel through solid stock is necessary within a cutter field. A rudimentary solution for rounding milling paths by means of digital filters to obtain harmonious and continuously tangent milling paths was presented. The material within a cutter field must always be removed completely. If a field is cleared out applying a recommended radial infeed larger than the cutter radius, stock will remain at several locations. This material is detected and its development prevented by means of appropriate manipulation of the milling paths.

The first decision to be made in connection with updating the metal blank is the choice of a suitable modelling method. However, this selection cannot be made solely with the isolated goal of updating the blank. The decision must take the entire integrated process sequence into account, from design to the roughing programme and up to and including HSC finishing. A BREP solid modeller was selected. A polyhedral representation of the surfaces accomplished with the aid of triangular meshes is fully adequate for computations, e.g. the subtraction of volumes required to update the blank. An essential advantage of making calculations with triangular meshes is their simplicity and ruggedness. If the BREP modeller is capable of accommodating triangular meshes as entities in its structure, the advantages of simple, highly accurate design and rapid, robust calculations are combined.

The task of updating a blank consists in subtracting a milled volume from the blank. The difficulty with this Boolean operation lies in computing the separating curves of

the two components, or in the unambiguous calculation of the lines of intersection between two triangles. Literature dealing with the subject pays a great deal more attention to the theoretical treatment of such geometric tasks than to the question of how to implement them. Usually, only the principle idea of the new algorithm is presented. But an extensive and detailed elaboration of all special cases and the observance of numeric inaccuracies are often necessary if one wishes to actually implement the algorithm. As in other areas of computer science, the principles of encapsulation of information and abstraction have proved to be of great assistance in ruling out numeric instabilities in the calculation of intersections. Topological primitives are used exclusively for computation. A topological primitive is a real-valued function whose input consists exclusively of geometric objects and that supplies three different signs (-1, 0 or +1) as calculated functional value. A special role is assigned to the result 0 of the topological primitive. It represents a special case that must be dealt with (e.g. two tangent triangles). These special cases are handled according to the Simulation of Simplicity statement predicated by Edelsbrunner and Mücke in [10]. The position and shape of the geometric objects that form the input of the topological primitive are the reasons for the existence of a special case. The general idea is thus to alter the position and shape of the objects somewhat (to perturb them) to eliminate the existence of a special case.

Although at the beginning of CAD development, there was still a strict separation among the most diverse options provided by 2D and 3D software, there is no longer a question today of one or the other. While a 2D system is sufficient for a simple workshop drawing, the future belongs to the 3D systems. In most cases, design is a mixture of 2D and 3D. And this is where it must be made certain that designs consistently remain free of errors when modified. This means that changes are completely updated, including all views and all dimensions.

New-generation CAD systems will be capable of supplying a far more comprehensive product data model. This means that integration will continue to gain importance in the future. Loss-free exchange of data will represent a major challenge for manufacturers during the coming years. The goal is the application of uniform data formats that ensure data exchange at all levels. This will remain necessary as long as heterogeneous CAD/CAM systems are employed for special applications. CIM used to be a catchword and it was primarily a matter of manufacturing aspects. Today simulta-

neous and concurrent engineering are the key phrases and it is all about central and uniform product data that are universally accessible to design and production departments. With regard to CAD, this intensifies the demands made on the exchange of designs between manufacturers and their suppliers. Thus it becomes more and more important that the CAD tools employed be available worldwide and that systems be capable of communicating with each other. In other words, standardisation will play an even greater role in the future. This includes integrated software that enables users to access the same uniform database for all applications.

Simultaneous engineering demands easy-to-operate systems. This includes a uniform user interface throughout the most diverse corners of the software. The system will offer the user identical operating techniques and interactive prompts at every location, making a highly closed and uniform impression in the process. It must be possible to carry out changes and modifications at any time without knowledge of the previous history of the current model or the prior manufacturing sequence, thus allowing the development and manufacture of a product within the same time frame, but at different times in several different countries.

Increasingly, companies are becoming aware that simply documenting a product in the form of electronic drawings cannot accelerate product development. Meanwhile they see the benefit for production above all in the fact that CAD data can be utilised as the starting point of a universal integrated process sequence for manufacturing.

Future CAD systems will have an object-oriented structure. This will conclude the transition from a geometry-oriented to a feature-based system. The advantage of such systems is they permit the incorporation of random production data into the product model in addition to the geometric figure itself. Technological and functional data such as tolerances and surface finishes are stored in the part description along with its geometric description. This enables downstream manufacturing processes to automatically take the part description into account. The transition from purely geometry-oriented CAD/CAM in die, mould and pattern manufacturing toward technology- and knowledge-based tools is already foreseeable today and will indeed happen. For this reason, the focus in the future must be on those product data models that permit a diversity of descriptive features in addition to geometry. But this also means that only 3D models will be used in the future.

The era of the dinosaur is drawing to a close in the CAD/CAM sector as well. Today's intelligent CAD/CAM systems no longer run on mainframe computers or costly workstations. As their performance ranges continue to expand, PC systems will continue to gain ground and edge the workstations out of the market. This trend will certainly be strengthened due to the attractive prices of PC systems, which cover a range clearly exceed by workstations. The CAD/CAM market of the future will lead to a concentration on the supply side. Above all, the vendor of CAD/CAM software must deliver performance that pays off for the customer in the short term at prices that neither of them would dare to even dream of today.

The refinement of the market will continue at an advanced pace. Only a few suppliers will remain a position to develop both modern basic technology and powerful applications. For this reason, component technology will be developed and utilised more and more. In this way, the volume core ACIS has gained acceptance as the standard geometry core for CAD applications, for example. Partnerships among application developers who possess the specialist know-how required to develop special-purpose and niche products will also become immensely significant.

The transition to which the CAD/CAM world, especially the die, mould and pattern manufacturing sector, is submitting itself today stems originally from two tendencies. On the one hand, there are new technological opportunities. On the other hand, the demands of customers are changing. The noticeable trend toward 3D solid applications is certainly technology driven. The mathematical descriptions of the parts, which serve as a basis for the NC programming systems used, are wire frame, surface or volume models. Part models generated by means of surface modellers frequently contain errors because gaps may appear between individual surface segments. Such gaps may result in the cutter unexpectedly striking the workpiece at the defective location. These gaps between surface patches and any tangential discontinuities must be eliminated in order to obtain satisfactory machining results later. The system may support the user in making such corrections or perform the corrections itself either automatically or semi-automatically. This problem is not encountered with volume-based systems because a volume model is subjected to a consistency check when it is generated and is therefore free of gaps. And, as explained in previous chapters, the volume model is the only model that permits exact updating of the workpiece upon completion of a step in the machining operation.

Collision analysis is a difficult chapter in the generation of NC programmes for rough machining. Although potential collisions between the cutter and the current blank can be detected using the proposed concept, this analysis must be extended to include collisions with tool-holders, the spindle head and work-holding fixtures. In the end, the entire machine tool must be imaged in a kinematical model and all components related to the roughing process in the CAD/CAM system. All of them must be checked for mutual collision at all times. This then corresponds to total collision control. The analysis may be supplemented by simulation and animation, which allow an examination of machine movements as early as the NC programming phase. In turn, this means that production-related aspects such as the selection of the machine tool must be taken into account during NC programming as well.

Appendix A

Software

The concept at hand was almost entirely implemented in software. The software was integrated into the Tebis CAD/CAM system Version 3.1 Release 10 which is used by more then 1300 customers as of April 2001.

The Tebis CAD/CAM system combines the necessary CAD functionality with all CAM commands essential for obtaining die, mould and pattern finishes. The CAD includes everything the designer needs, e.g. commands for rounding, offsetting, tangential attachment, slizing and trimming, structuring, analyzing and documenting. The CAM functionality provides all commands required for NC programming in a compact and user-friendly form. The system generates programs for roughing and finishing, for remachining fillets and clearing areas of residual stock , for trims and HSC operations.

The software implemented by the author of this thesis can be found within the Tebis CAM module for roughing in layers. On the basis of the blank and specified geometries, the software automatically generates tool- and machine-friendly NC programs for roughing in planes that produce components with a steeped appearance. At the early stage of toolpath computation, the geometry of the blank is updated plane by plane with reference to the roughing tool used and the selected strategies. The intermediate geometry produced in this way can be used for analysis and post-roughing purposes. The keynotes of the software are short machining times and paths that inherently reduce tool wear.

Because of the high diverse product spectrum in the die, mould and pattern manufacturing industry, no specific examples of NC programs are given in the thesis. Rather the reader is invited to use the software focusing on his or her special interests.

The CD ROM, which is fixed to the last page of the thesis and named Tebis Version 3.1 Rel 10, contains the whole Tebis CAD/CAM package. To run the software, the hardware must consits of either:

- An upgraded 32-bit personal computer with up to 1GB of main memory and a hard-disk capacity of several gigabytes.

- A UNIX workstation.

The graphics unit consits of a high-end graphics card with OpenGL support and a high-resolution color graphics monitor capable of at least 1280 x 1024 pixels. A series of additional peripherals can be connected for the input and output of external data.

A dongle has to be used to run the software because Tebis needs to protect the software against unauthorized copying. To get such a dongle, please contact the author of this thesis at the following address:

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