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An approach for systematic process planning of gear transmission parts

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Abstract

The objective of this thesis is to find and develop methods that enhance and support the creation of evolvable master process plans with possibilities to challenge productivity and meet changing design requirements. The condition for achieving this is primarily that both the fundamental thinking and the results behind a process plan can be described. How should this be done?

The focus is laid on process planning of gear transmission parts for heavy vehicles like trucks and coaches.

Process planning is the activity where design and manufacturing are brought together with the common target to achieve both a competitive product and production process. There are many factors that influence the process planner when a new product or process shall be introduced for production. Process planning is, in most cases, performed by an experienced, skilled person but without any defined methodology or way of working. Much of the process planning is based on the retrieval of solutions already used.

Much research effort has been devoted to developing systems for computer-aided process planning (CAPP). Yet CAPP systems have not been accepted and spread over a wide front within the manufacturing industry, much because of the functional incompleteness combined with the difficulties of adopting knowledge and changing requests.

A method for systematic process planning is proposed as a way to perform and describe the procedure of creating a process plan. The method facilitates the interpretation and understanding of the plan, not only immediately for the process planner responsible, but also for designers, engineers, researchers and other interest groups involved in a manufacturing process.

In the last chapter is a case study regarding manufacturing of a bevel gear pinion presented to exemplify use of the proposed method for systematic process planning.

Preface

This thesis is a result of the work performed at Scania CV AB, Department of Axle Production in Södertälje, Sweden and Royal Institute of Technology (KTH), Department of Production Engineering in Stockholm, Sweden, within the “KUGG” project. KUGG is a collaboration project between the leading gear manufactures, tool manufactures and other suppliers in Sweden, founded by VINNOVA – the Swedish Governmental Agency for Innovation Systems.

Many of the ideas that have ended up in the problem formulation for this thesis have been accumulated during years of working with production engineering and process planning at Scania CV AB.

I would like to thank my supervisors Bengt Lindberg and Sören Andersson at KTH and Ulf Bjarre at Scania CV AB for their enriching support and adding stimulating viewpoints from their own experience and areas of interest.

Finally, I would like to show my gratitude to Carolin and Hanna for your help and love!

Mats Bagge

Södertälje, January 2009

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PART I

PART I

1 Introduction

This introductory chapter describes the background and objective to the presented research. One section covers previous research in the process planning area. A gap-analysis is made to identify what has to be done to achieve the objective. Finally, the outlines and delimitations of this thesis are defined.

1.1 Background

In every situation when a new product is to be manufactured, there must be several decisions made by someone with process planning skills about how this shall be managed. Process planning is important work because it significantly influences the cost of components and it affects company competitiveness, production efficiency and quality of the product (Helevi and Weill, 1995). – *How should a well worked-out process plan for transmission parts be drawn up?*

The role of a process planner can briefly be described as a link between design and manufacturing. The responsibility is to establish and maintain good connections for interchanging and solving technical problems concerning production. The goal is to reach solutions that satisfy both design requirements and prerequisites for sustainable production. A process planner must, in that respect, be the expert and speaking partner concerning manufacturing. – *How can a process planner be well up in a certain planning case and confidently argue for essentials?*

Gear production is an area where the process planner is an important person due to the close relationships between gear design and manufacturing methods. Gear geometries are associated with complicated generating kinematics (Bouzakis et al., 2008). Machining and measuring possibilities define what the gear designer has to deal with. The complete gear part (gearwheel, shaft etc.) is produced using both machines and tools that are specially developed for gear manufacturing, and with standard machine tools for common methods like turning, hardening and grinding.

It is a symbiotic development within this area. Both gear design and manufacturing have a fixed purpose, to achieve higher performance with the gear. This implies the need for efficient process planning tools and methods which can manage the characteristics of gear part production. – *How can the entire part be process planned in an efficient way?*

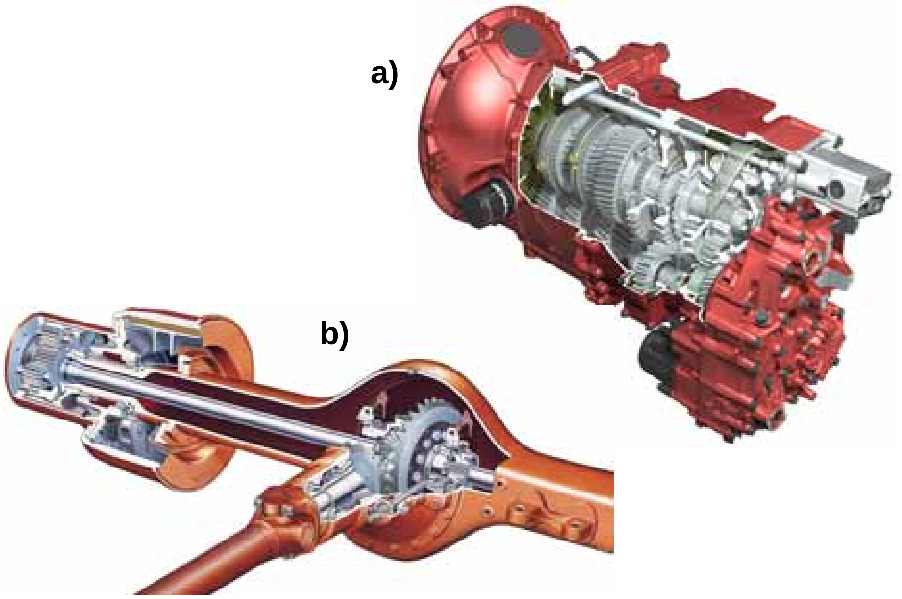

Figure 1-1 Drive train gear transmissions for heavy trucks.
a) Scania GRS905R 12+2-speed gearbox with Scania Retarder
b) Scania single drive axle
(Illustrations from Scania CV AB).

This thesis examines process planning and manufacturing of complete gear parts used for heavy trucks[1], buses and coaches. Typical applications are gearboxes and axles shown in Figure 1-1.

1.2 Previous research

Many researchers and authors of technical literature describe and try to develop process planning from different viewpoints and with different objectives. There is a wide range of approaches, all with the intention of making process planning easier and more time efficient.

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[1] Gross vehicle weight of more than 16 tonnes.

Since the 1970s, much research has been concerned with finding techniques and methods that facilitate the use of computers for process planning, generally called “CAPP” (ElMaraghy, 1993).

1.2.1 CAPP

When “Computer Aided Design” (CAD) and “Computer Aided Manufacturing” (CAM) were introduced and accepted as common tools, there was a gap left between them (Joseph and Davies, 1990). The available CAM-software was practically generating programs for numerical controlled machine tools by transforming CAD-data to tool-paths. Process planning, like the choice of machining processes, manufacturing sequence, fixturing, tolerances etc. was not covered. This work was still required and needed to be “computerized” to integrate CAD and CAM (Jeang, 1999; Crow, 1992). In conformity with the abbreviations CAD and CAM “Computer Aided Process Planning” - CAPP – was introduced. CAPP has been a research topic since 1960s (Zhang et al., 1989).

The following is a description of CAPP in five stages, mainly based on Helevi’s and Weill’s (1995) review of the gradual CAPP development.

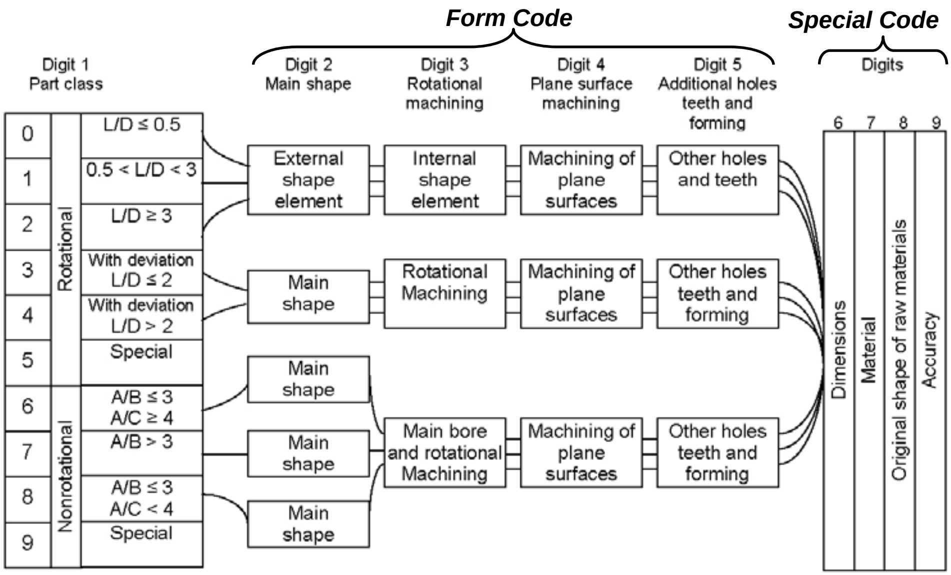
CAPP stage 1: “Computerization of files management”

The idea is to minimize the clerical work for the process planner, leaving her/him free for technical work. A computer in this stage is only used for sorting a database that has been filled with content by the process planner.

CAPP stage 2: “Variant (retrieval) approach”

This approach is comparable to the traditional manual way of working. Similar parts are assumed to have similar processes. A process plan for a new part is created by first recalling, identifying and retrieving a plan for a similar part. Required modifications are then performed to suit the new part (Gawlik, 2002). In this case, a computer helps to identify and retrieve the information from a process plan database.

The variant approach is derived from Group Technology (GT) methods (Kuric et al., 2002). One example of a Group Technology classification system is illustrated in Figure 1-2.



Digit 2

Code		External shape, external shape elements
0		Smooth, no shape elements
1	Stepped to one end	No shape elements
2	Stepped to one end or smooth	Thread
3	Stepped to one end or smooth	Functional Groove
4	Stepped to both ends	No shape elements
5	Stepped to both ends	Thread
6	Stepped to both ends	Functional Groove
7		Functional cone
8		Operating thread
9		All others

Digit 3

Code		Internal shape, internal shape elements
0		No hole, no breakthrough
1	Smooth or Stepped to one end	No shape elements
2	Smooth or Stepped to one end	Thread
3	Smooth or Stepped to one end	Functional Groove
4	Stepped to both ends	No shape elements
5	Stepped to both ends	Thread
6	Stepped to both ends	Functional Groove
7		Functional cone
8		Operating thread
9		All others

Digit 4

Code	Plane surface machining
0	No surface machining
1	Surface plane and/or curved in one direction external
2	External plane surface by graduation around a circle
3	External groove and/or slot
4	External spline (polygon)
5	External plane surface and/or slot, external spline
6	Internal plane surface and/or slot
7	Internal spline (polygon)
8	Internal and external polygon, groove and/or slot
9	All others

Digit 5

Code		Auxiliary holes and gear teeth
0		No auxiliary hole
1	No gear teeth	Axial, not on pitch circle diameter
2	No gear teeth	Axial on pitch circle diameter
3	No gear teeth	Radial, not on pitch circle diameter
4	No gear teeth	Axial and/or radial and/or other direction
5	No gear teeth	Axial and/or radial on PCD and/or other directions
6	With gear teeth	Spur gear teeth
7	With gear teeth	Bevel gear teeth
8	With gear teeth	Other gear teeth
9	With gear teeth	All others

Figure 1-2 A Group Technology (GT) system.
On top: The Opitz parts classification and coding system.
Below : The available form codes (Digit 2-5) for part classes 0-2 are shown as an example. The illustration is based on figures by Girdhar (2001).

Accordingly to Opitz parts classification and coding system in Figure 1-2, the part is described by a nine-digit code like “254102273”. Each digit represents an attribute of the part e.g. length/diameter ratio (L/D), external shape elements or material characteristics.

The idea of GT is to classify and code machined parts into part families. A family covers parts having attributes sufficiently similar to prescribe a common manufacturing method. Each family has a standard process plan, including all possible operations, that is stored in a database. The standard plan is retrieved and edited for the new part.

The computer is just a tool used to assist the manual process planning activity. According to Helevi and Weill (1995) and Gawlik (2002), the result when using this approach is still dependent on the background and skills of the process planner.

Helevi and Weill (1995) also state that the advantages compared to manually process planning are:

- Uses existing company manufacturing data and competence
- Frees the process planner from routine clerical activities
- Applies to all types of manufacturing
- Is capable of updating and reflecting changing manufacturing technologies for new and old parts
- Incorporates company standards
- Process plans a complete part

The goal is to define optimized master processes that fulfil the company strategy.

CAPP stage 3: “Variant approach - enhancement”

The classification system described above is a “stiff system”. New data and characteristics may be added but changing in the system is difficult (Helevi and Weill, 1995).

Decision tree, decision table and expert systems are some methods described aimed at enhancing the variant approach

However, a computerized classification system supported by e.g. a decision tree may allow flexibility, but just within a limited extent.

A rearrangement of the families requires due to Helevi and Weill (1995) a reorganization of the master process plan files.

CAPP stage 4: “Generative approach”

This approach is thought to be a tool for fully automatic process planning.

A computer program generates a complete process plan by means of technological algorithms, decision logics, formulae and geometry base data. Manufacturing know-how and capabilities of the processes are entered into the system resulting in the possibility of generating a specific plan for each part. If any input is changed, like availability of a certain machine tool, alternative process plans can be generated.

A part description can be put in as either text or graphic CAD-data (Gawlik, 2002). A solid CAD model is preferred since this is an unambiguous description of the part (Kuric et al., 2002).

The generative approach is complex in terms of the extensive range of algorithms, decision logics, formulae and data that replace the mind and knowledge of a human process planner. That makes the generative approach difficult to develop (Helevi and Weill, 1995).

CAPP stage 5: “Semi-generative approach”

Because the “Generative approach” (CAPP stage 4) is not fully developed, there is still a need for some manual process planning work. The “semi-generative approach” is defined as a combination of the generative and the variant approach. An advanced application of the variant approach is supplemented with features from the generative approach and human process planning interpretations and decisions (Gawlik, 2002).

The process planner must co-operate with the CAPP system to get a complete process plan ready for production.

1.2.2 Other areas

Different “Artificial Intelligence” (AI) approaches has been developed, evaluated and described for many process-planning tasks. “Case Based Reasoning” (CBR) and “expert systems” are commonly used in many CAPP systems. Examples given on research performed in this area are Chen et al. (2005), Zhang W. Y.(2006), Zhang K. F. et al. (1989) and

Mamalis et al. (1994). Both CBR and expert systems are knowledge-based systems, which in principle contain the knowledge and analytical abilities of one or more process planners. Compared to expert systems, CBR-systems have the capability of learning and to being in domains with limited knowledge or knowledge that is not understood. The CBR-system can improve its skills with more experience in form of new cases (Champati et al., 1996).

Tolerancing has always been one of the most important tasks during process planning, especially when the manufacturing processes are appreciated due to their capability[2], which has the tolerance width as numerator. Many research topics during the last few years have been about tolerancing and how to optimize for maximum capability and/or cost (Farmer and Harris, 1984; He and Gibson, 1992; Lee et al., 1999; Dantan et al., 2007; Jeang et al., 2007).

Graphical methods such as "Rooted-tree" and "Datum-hierarchical tree" are introduced as techniques for easier handling of tolerance stacks than the commonly used tolerance-charts (Whybrew et al., 1990; Britton et al., 1996; Thimm et al., 2001; Britton, 2002; Gao and Huang, 2003).

Stampfer (2005) discusses planning systems for set-up and fixturing. Paris and Brissaud (2005) present a strategy for process planning which focuses on part quality depending on fixturing.

All these works have been produced to develop efficient methods for process planning and some of them illustrate the close relationship between engineering design work and process planning in terms of manufacturability (Farmer and Harris, 1984; Thimm et al., 2004:1-2; Jeang and Chang, 2002; Jeang and Hun, 2000).

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[2] Capability can be expressed as an index $C = \frac{T_u - T_l}{6 \cdot \sigma}$ where:

T_u=Upper tolerance limit
T_l=Lower tolerance limit
σ=Standard deviation

(Bergman and Klevsjö, 1995)

1.3 Gap analysis

In general, the previous research objectives are found to consider sub-areas of the entire process planning range. Examples are the analysis of fixtures, tolerances or certain machining operations. These are useful but must be applied in an all-embracing technical context.

According to Helevi and Weill (1995), the development of generic programs and structures for computer aided process planning has predominantly been performed by computer experts or experts in the area of artificial intelligence. This has been resulting in systems that lack sufficient relevant process planning techniques and intelligence. In spite of the fact that many CAPP systems have the all-embracing approach, much of the logic behind process planning has not been caught and implemented.

By studying the works of researchers and writers, it is evident that it is a difficult task to define and describe how process planners perform their work. Each process planner expert has his/her own experience, intuition and way of thinking. This makes it difficult to find a common accepted methodology that can shed light upon the underlying thoughts during process planning (Helevi and Weill, 1995). Probably, this is one of the reasons why CAPP-systems suffer from not having sufficient process planning logic.

Some of the works contribute to the structuring of process planning in the context of tolerancing. These ideas are partially used in this thesis to identify and analyse relationships between operations.

In contrast to much of the last few decades of research and development in the process planning area, the intention of the approach presented in this thesis (chapter 4) is primary *not* to act as a structure for *automatic* planning. However, the result can be an important input for developing and using CAPP-methods. This is because of the higher level of process planning understanding that can be gained by using the proposed method.

1.4 Research objective and question

The purpose of this work is to find and develop methods that enhance the process planning of transmission parts. These methods shall be capable of supporting the creation of evolvable master process plans with the possibility to challenge productivity and meet changing design requirements.

The conditions for achieving this are that both the results and the fundamental thinking behind a process plan can be described. The interpretation and understanding of the plan will be easier, not only immediately for the responsible process planner but also for other relevant interests involved in the manufacturing process.

Finding methods that can support this is also important for the understanding of the process planner's way of working. The possibility to describe process planning is essential when the working methods shall be developed and improved.

The gear geometry can be both designed and process planned as a separate feature of the part. This does not support the importance of considering the complete transmission part during process planning. Working methods that facilitate the integration of process planning of the gear geometry with the complete transmission part are advantageous.

What must be done to reach these objectives? This is expressed as the research question:

How can process planning of transmission parts be systemized and transparently described?

1.5 Delimitations

This thesis will focus on the process planning of gear transmission parts for powertrains, especially those intended for use in heavy trucks, buses and coaches.

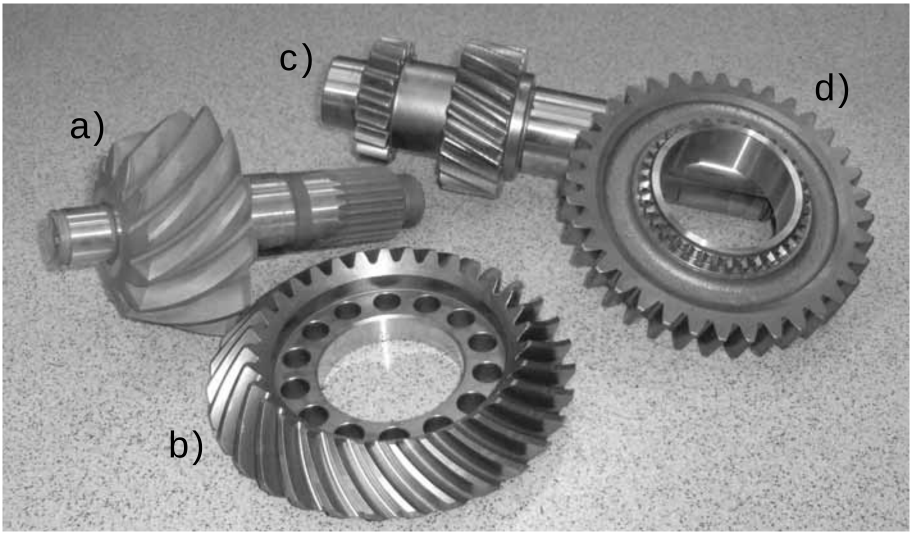


Figure 1-3 Typical gear transmission parts.
a) Pinion and b) Crown wheel (both for a rear axle)
c) Lay shaft and d) Gearwheel (both for a gearbox)

Typical transmission parts are shown in Figure 1-3. These four parts are chosen as being representative of what is used in a gearbox (gearwheel and lay shaft) or central gear in a front or rear axle (pinion and crown wheel).

Detailed tolerancing is a topic not dealt with in this thesis, but discussed as an important part of the complete process plan.

Mainly machining and some kinds of typical treatment for transmission parts will be considered later on as industrial production and subjects for the process planning. E.g. assembly is not dealt with.

This thesis focuses on technical issues that must be considered when carrying out the process planning work; independent of a certain company's organization or job definitions.

2 Research approach

This chapter describes the scientific approach that has been used in this thesis.

The research approach used in this thesis is built on a foundation where the aim is to include experiences, procedures, ideas and practical data in a system that can be described, understood and developed. This is one attempt to connect practice and theory within the process planning domain.

2.1 Induction and deduction

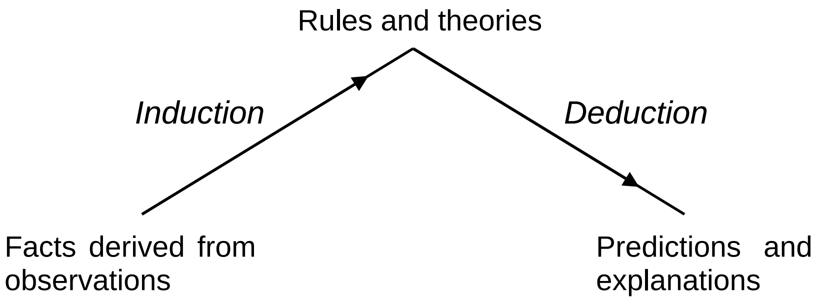


Figure 2-1 Induction and Deduction, as illustrated by Chalmers (1999).

"Induction" and "deduction" are two different ways of reasoning in the scientific research area. The principle of induction and deduction is illustrated in Figure 2-1 and explained as follows:

- Induction is the building of general theories based on conclusions drawn from a limited number of observations.
- Deduction is reasoning where the conclusion is drawn as a logical consequence from a number of premises.

2.2 The experiential researcher

Wigblad and Jonsson (2007) define a research concept that contains both theoretical and empirical methods with a strong, knowledge based practical origin. An experienced, intellectual person with intimate reflected knowledge is performing the research and is called “experiential”. The experiential researcher uses neither induction nor deduction but “abduction”.

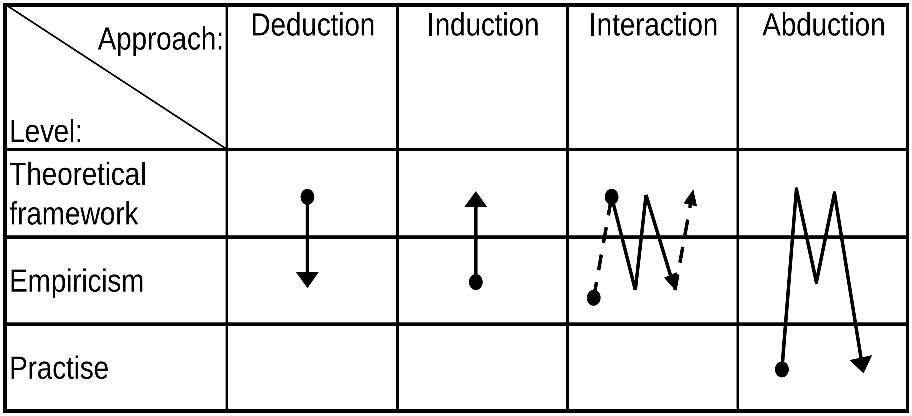


Figure 2-2 Comparison of typical choices of research methods. The illustration is adopted from Wigblad and Jonsson (2007).

Abduction is often described as something that is interacting between induction and deduction. Wigblad and Jonsson (2007) describe abduction in an extended way where reflected knowledge, gained from well-proven practical experience, is the start and base for the research. The research goes via interaction between theory and empiricism back to the practise level as illustrated in Figure 2-2. The results are often action oriented and contain new and profound knowledge.

2.3 Positioning of this thesis

The research presented in this thesis is in many ways performed according to the “experiential researcher” approach by Wigblad and Jonsson (2007). The extended definition of abduction shows the principle of three-level interaction between practise, empiricism and theory and is comparable to the research performed.

The source of information in this thesis is the practical level. The need for new knowledge in the area of process planning is drawn from the practical level.

The process planning actions have to be identified, well defined and put into an understandable system. This will be the approach to delve deeper into the process planning domain.

By defining a method for systematic process planning, the step is taken to the theoretical framework level. A foundation for further work is established. This is an approach for handling the very broad subject of process planning which is hardly explained and described in a general way.

The creations and experiences of both craftsmen and engineers that are needed for process planning can then be identified, evaluated and improved by scientists. This is in line with the Saito´s (Saito, 2006) description of the relationship between craftsmen, engineers and scientists: "…the craftsman's role is the same as the engineer's role in creation and problem solving, while a scientist's role is needed here to understand why the solution worked."

Initially, the role of the process planner must be described and defined. This makes it possible to find out in what situations a method for process planning shall be applicable. In addition - what are the inputs and outputs?

The thinking, logic and systematic behind a process plan must be emphasized and caught by the method. The resulting process plan must be transparent for further observation.

The aim is threefold and each aim is related to the levels defined in Figure 2-2 as follows:

1) Contribute with a definition and systemized structure of the process planning domain.
   - Theoretical framework level

2) Get a platform for empirical evaluation of process planning
   - Empiricism level.

3) Provide a usable tool for practical process planning work.
   - Practise level.

3 Process planning

This chapter provides an introduction to process planning and guides the reader through the area of this subject. The characteristics of process planning for machining in general and the topics a process planner within gear manufacturing has to face in different situations will also be described.

There are many different situations where some kind of work is done to transform a description of a product into a "how to make it" plan. A wide range of technical, personal and strategic conditions will surely affect this plan. The work to consider all these aspects and define the best way to manufacture a certain product under given circumstances is herein called process planning.

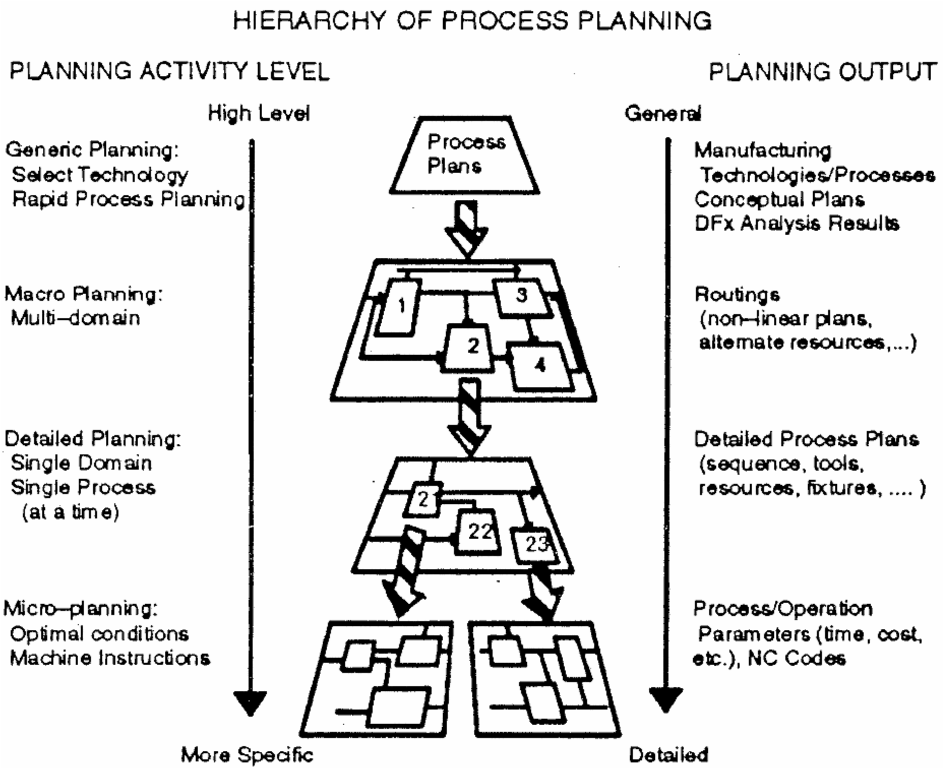


Figure 3-1 Types and levels of process planning activities and their outcome. ElMaraghy (1993)

Figure 3-1 shows process planning activities and their outcomes classified into different levels of detail. This description is given by ElMaraghy (1993) and is suitable as a general overview of the activities within the process planning domain. The situation of the process planner who performs these activities is described in the next section.

3.1 The process planner

The technical context in which a process planner takes an active role can be illustrated as shown in Figure 3-2.

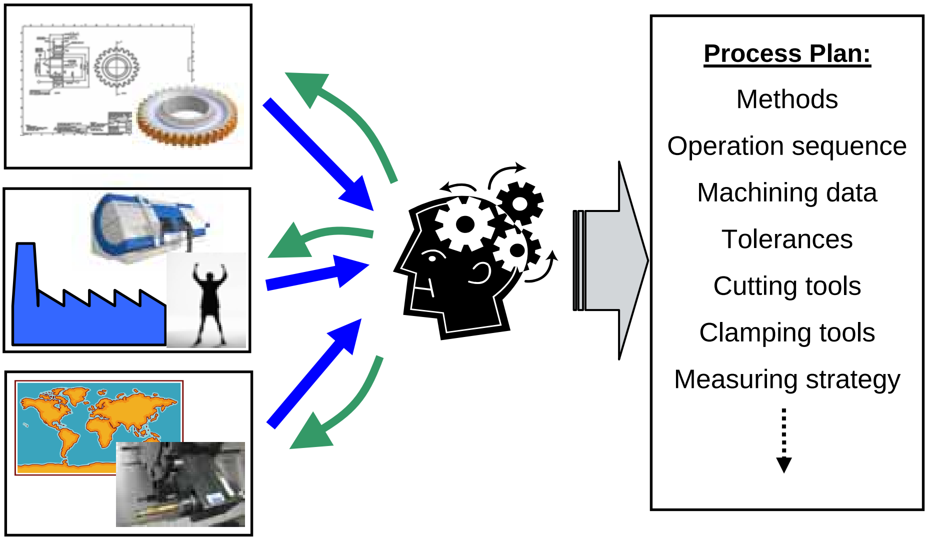


Figure 3-2 The process planner

On the left hand side in Figure 3-2, there are three areas of interest symbolizing the process planner's sphere of activity. These are collaborators during the development of new process plans or the revision of present plans. The process planner needs to get inputs from all three areas and has to feed process-planning aspects back in an iterative manner.

- Uppermost, the gearwheel drawing represents the resources and organization for product development.

- In the middle, a workshop together with a machine tool and person symbolizes the available manufacturing resources, capabilities and competence.
- At the bottom, a map showing the world around which technical solutions and methods can be provided.

The box to the right in Figure 3-2 illustrates the product of the planners work, typical contents of a process plan for the manufacturing of transmission parts.

A nomenclature statement about “drawing”. The design of a product must be defined and described in some way. A typical representation is by a two-dimensional (2D) drawing, sketch or figure. More and more common is that design work, calculations, simulations and process planning are performed with three-dimensional (3D) CAD models. Further on in this thesis “drawing” will refer to a 2D representation of a part. It is unessential whether the drawing has its *origin* in a sketch, 2D or 3D model.

3.2 The process planner within concurrent engineering

The development and introduction of new products is often a process where the working principle called Concurrent Engineering (CE) is used. Concurrent engineering is characterized by an organization where niche professionals are responsible for a variety of development tasks, which are executed concurrently, that is to say with the same pace.

The development in this case includes both the product and the manufacturing system aimed for use in its production. Concurrent engineering is used to increase productivity and quality not only of the product and manufacturing process, but also of the development process (Aganovic, 2004).

CE is a method for cross-functional work, which can be applicable through the entire lifecycle of a product.

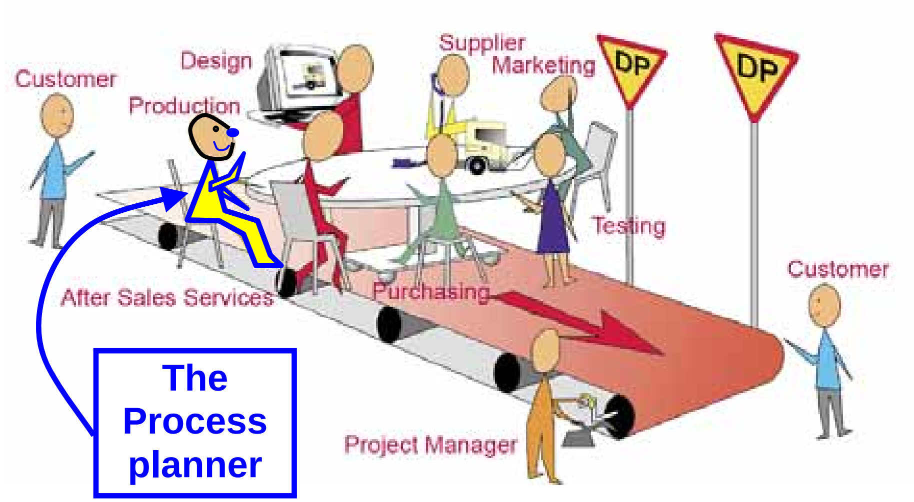


Figure 3-3 Cross-functional and parallel work. (Source: Scania CV AB)

Concurrent engineering is illustrated by Scania CV AB as shown in Figure 3-3.

Traditionally the designer finishes his/her work and hands over a drawing to a process planner in the workshop. In CE, the process planner is an important participant who must take active responsibility for manufacturing aspects from start. In a new product project, the focus is on affecting the design in a way that leads to good manufacturing abilities and capable processes.

The contribution from the process planner within CE is important. The conditions for this work must be supported by good methods for the analysis and evaluation of both design data and manufacturing resources.

Drawings and other documents that represent the design are essential as carriers of information. There is also a lot of other information to be exchanged such as time schedules, risk analyses, cost prognosis etc. It is always preferable to have a good dialogue and establish good interpersonal relationships within the project. To support these relationships and involve all professionals is one of the main tasks for the manager of such CE-development projects.

3.3 Mission of process planning

-What is the role and mission for a process planner in the context described?

A simplified picture of a typical situation where a *new* product is introduced can be described as follows:

There is in any case the new product, or thoughts about a new product, that initiate the work to draw up a process plan. This is symbolized in Figure 3-2 as an output arrow from the product development, addressed to the process planner. For example, this consists of ideas, drawings or data from the designer that represent the product.

In most cases, there are existing resources for manufacturing available that the planner must be aware of. These are shown as an output arrow from the manufacturing resources in the figure.

The process planner interprets the design requirements and investigates if it is possible to make the product in the available workshop. Most of the time at this stage, there are many questions that must be answered. This implies different kinds of investigation to solve the task.

It may be necessary to make improving changes on the design or the manufacturing environment, in many cases both. This results in feedback from the planner to the product developer and the manufacturer.

Sometimes there is a need to introduce new manufacturing solutions or methods to reach the required quality, efficiency or a new product range. This leads to an interaction between at least suppliers and the process planner.

The mission for the process planner, and the general goal for all industrial process planning work, is to at least transform the agreed requirements of the product into a definition of a proper process. This definition shall state in detail how the product should be manufactured with the “right quality” in combination with the lowest cost under given circumstances.

“Right quality” is mainly related to customer demands but it has to be transformed, defined and decided by means of tolerances on a part drawing and requirements for the manufacturing process. Further on, “right quality”, or just “quality”, will basically correspond to all the requirements that are stated on drawings, data sheets, in models or other documents that defines the final product.

Depending on what kind of products and markets a company has, the recurring process planning work can be seen as rather different tasks. A company that makes small batches of different products from time to time compared to a company where a few products are produced in high volumes shows a difference in how process planning is carried out.

Within the workshop of the latter company (with high volumes and few products) there are a limited number of different machine tools where each machine tool is targeted for a specific range of operations. One can assume that these machine tools more or less fit the needs of that certain company with its specific range of products. The constraints of available resources and the characteristics of the products allow the process planner to standardize, simplify and rationalize his work in a different way compared to diverse production in highly flexible equipments.

Basically, there should not be any differences in how to present a new product for production. The fundamentals are the same but there are many ways to practically manage this work in terms of guidelines, IT solutions and strategies.

If the product design is mainly defined by parameters and is usually changed, then process planning can be drawn up in terms of parameters. For example, companies developing and producing cutting tools to customer order practice this.

In all cases and as a first step, there has to be an underlying technical investigation and analysis founding some kind of knowledge which further on can be used as:

- feedback to designer
- feedback to workshop
- feedback to machine tool supplier
- input when building up a single process plan, master plan or a systematic method for process planning

3.4 The intention of a particular process plan

As previously mentioned, there are many different conditions for what a process plan should fit. For example, a large, diversified workshop containing many different machine tools for a wide spectrum of products, or a smaller workshop with just a few machine tools specialized for turning.

Depending on what development and design stage a product has reached, the possibility of influencing the design varies. This means, in some cases, the objective for a process planner should be to adapt the manufacturing process for producing a certain “unchangeable” product. This is often the case for external subcontractors. Especially when the product design is reaching the end of its lifecycle, there will be lack of enthusiasm and resources to make design changes.

There can be situations where production flows must be changed due to new strategies and layouts for the workshop, due to changeover to new machine tools, or because of a machine tool breakdown. This requires at least an update of the process plan.

Another situation is when a new product development project is running and the design can be changed and adapted to an existing manufacturing process. In this case one question must be raised:

- Is the present process adequate for this new product’s lifetime in production, or should the design be made with other aspects in mind?

For example, a machine tool that has been in production for many years, and from the beginning was poorly dimensioned for the task, should not be set as a norm for the tolerances for a new product. The production may under special circumstances run in this machine tool but with care and awareness of the consequences. This question, in addition to others, has to be raised and answered by the process planner.

3.5 Design documentation

There must be some kind of description of the part to make. An adequate representation of the product is necessary.

Design drawings or product models in 2D or 3D show the geometry of a part and allow the designer to define requirements like tolerances, material, treatments and other parameters that are crucial. As stated earlier, these will be generally termed as drawings.

In early stages of a new product project, there are often conceptual drawings or sketches that describe the ideas and geometries of a part. Later on, these are revised with more accurate and well-evaluated requirements and finally they will be approved for the start of production. From the start of the project to the introduction of the product, the data represented as some kind of sketch or drawing is an important interface between the designer and process planner.

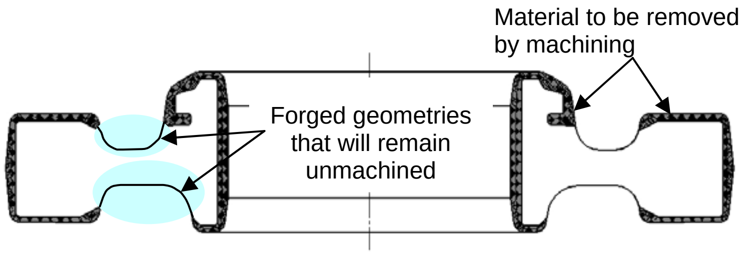
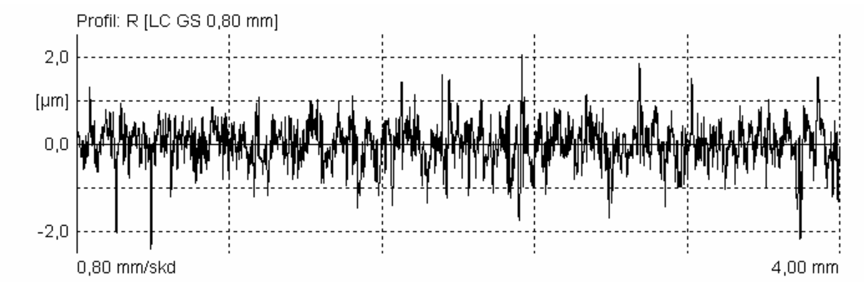


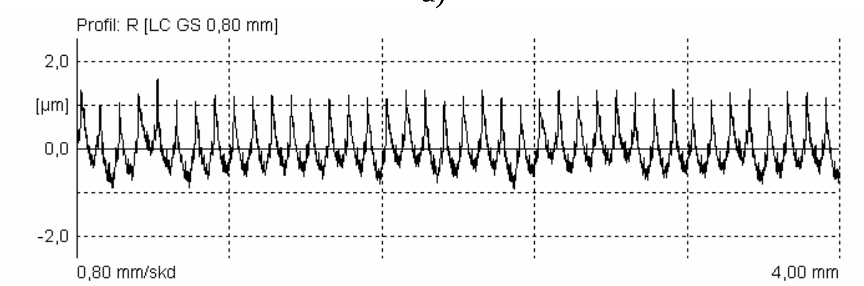
Figure 3-4 Drawing of gear blank. The blank partly represents the geometry of the finished part.

In some applications, the geometry of a blank represents more or less the geometry of the finished part. See Figure 3-4. This is one reason why it is important to interpret the definition of the blank drawing besides the design drawing. In practice, some kind of blank is always required as raw material for the process, and that will affect one or more operations.

A product design is often not completely defined by dimensions and tolerances but by the manufacturing methods that are commonly used for a certain purpose. For example, surface roughness can be, and often is, defined as an Ra-value (Svensk Standard SS-EN ISO 4287, 1998).



a)



b)

Figure 3-5 Two different surfaces with the same Ra, but different profiles and characteristics.
a) Grinding: Ra=0.35 ; Rz=3.44 [µm]
b) Hard turning: Ra=0.35 ; Rz=2.20 [µm]

A certain method like grinding with conventional ceramic grinding wheels, reaches some characteristics of the surface that can be measured in terms of Ra. Another method like hard turning can be set up to give the same values for Ra but different functional characteristics of the surface. As exemplified in Figure 3-5, the Ra-values are identical for a) and b) whereas Rz differs significantly. The profiles and functional characteristics are different.

In this opinion, the design documentation of a product does not fully define the required quality. However, with a certain process the required aims may still be fulfilled. There are standards for definitions and measuring methods which cover many functionally related aspects. These are more and more commonly used in new designs. Older ones often just have Ra and/or Rz. The definitions of Ra and Rz are illustrated in Figure 3-6.

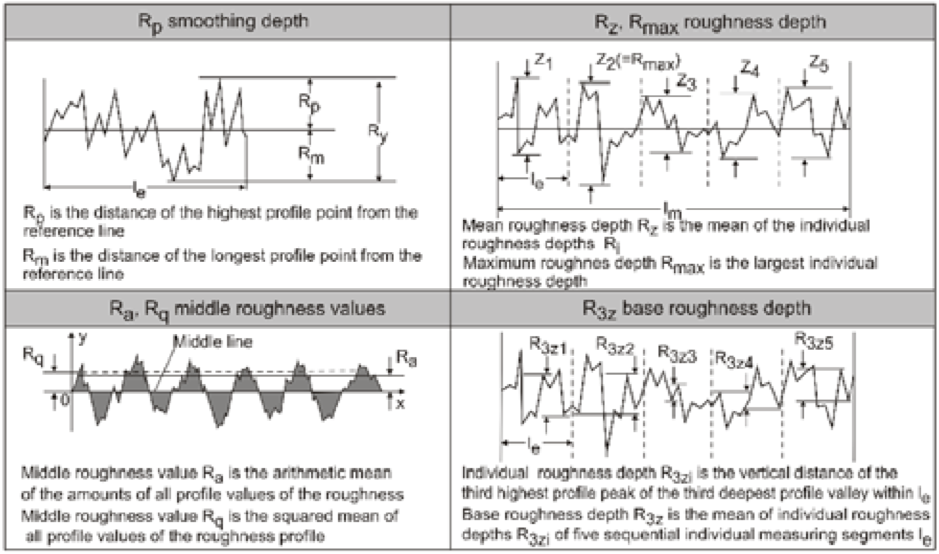


Figure 3-6 Definitions of surface roughness parameters. (Source: WZL, RWTH, Aachen)

Even though there are many ways to define the characteristics of a part, often supported by standards, there can be uncertainties when the manufacturing method shall be decided for the first time.

The same problem may appear when changing methods for a part in production or in connection with outsourcing. This is typically a matter regarding requirements on surfaces. The reason is that one method that gives some characteristics to the surface, has been used for a time and fulfils the functional aims. On the design drawing Ra and Rz may be stated for defining the surface, but the method is not mentioned despite it being found as essential.

Generally, it is preferable to develop a design drawing that completely specifies the part to obtain freedom when choosing manufacturing methods. This requires much effort both from the developer of the product and the process planner to obtain sufficient knowledge and data about how to specify all functional requirements. This implies that the requirements on the manufacturing process in some aspects may increase due to a more precise specification of the part.

4 A method for Systematic Process Planning

This chapter presents an approach to a method for the Systematic Process Planning of transmission parts. The benefits are of a technical, comprehensible and communicational kind. The focus is to describe a framework that facilitates the use and further development of the method for the intended purposes.

The approach for Systematic Process Planning presented in this chapter aims to support the possibilities to structure, identify, examine and evaluate details step by step but with a good overview. It will also facilitate easier process planning when single or extensive changes are introduced on a product or in a manufacturing process. In addition to the possibilities to establish documentation of the technical reasoning this will provide a way to describe the process planning work.

The substance of the methodology is mainly derived from process planning experience and put into a structured context aimed at satisfying the objective of this thesis.

The following items are identified as benefits that can be achieved when using the systematic method for process planning described in this thesis:

- Provides a way to describe process planning in detail
- Gives an overview of a complete process plan
- Facilitates easier analysis of each operation
- Provides basic data for decision-making
- Supports knowledge transfer
- Facilitates manufacturing (process) FMEA[3]
- Develops process planning progress reports
- Establishes documentation showing origin of decisions

[3] FMEA = Failure Mode Effect Analysis.

An important principle is the way the schematic process plan is created. The starting point is the *last* operation in the *manufacturing* sequence. The workflow of the process planning is then in the opposite direction to the manufacturing sequence as illustrated in Figure 4-1 below. This procedure is further used in chapter 4.2 about “The schematic plan”.

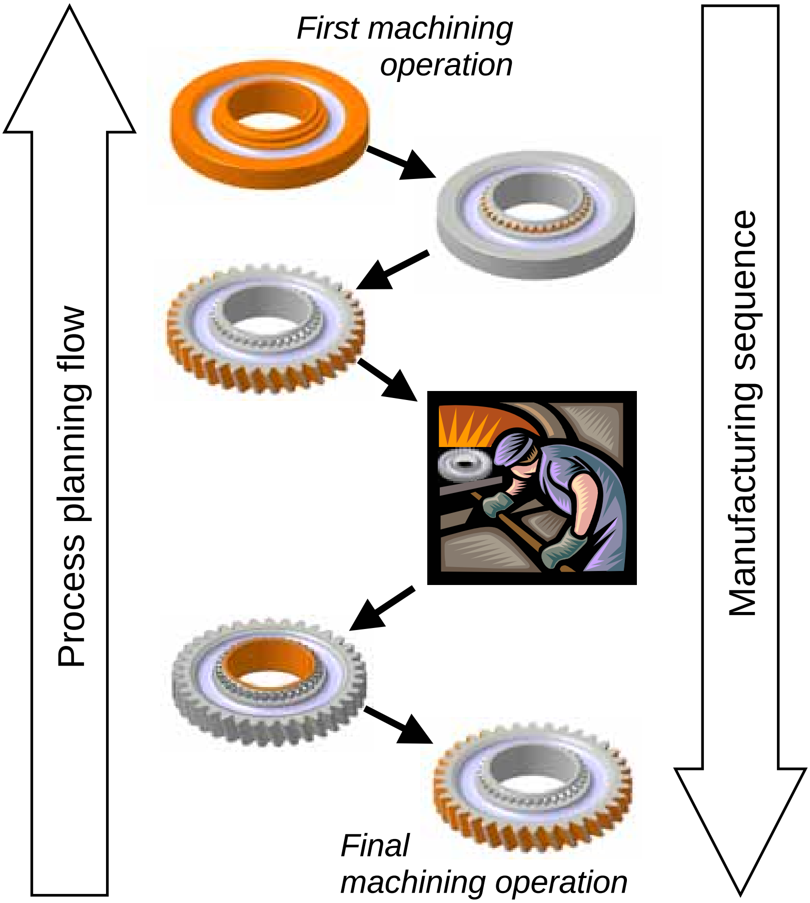


Figure 4-1 Process planning flow versus manufacturing sequence.

The outline of the procedure is shown in Figure 4-2 below. Each step is explained in the coming sections. The Figure 4-2 will be re-used in the beginning of the sections to demonstrate how the work proceeds.

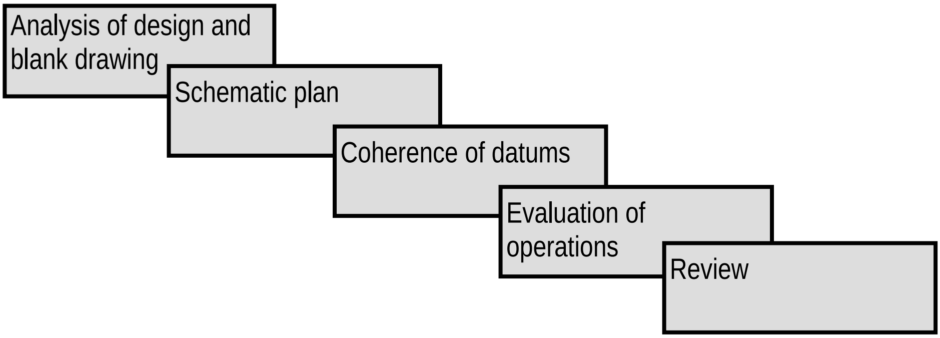


Figure 4-2 Procedure for Systematic Process Planning.

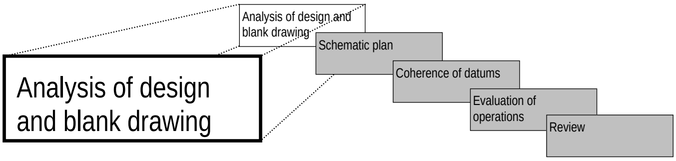
Different colours will be used for indicating and highlighting essential entities like datums and machined surfaces on drawings and sketches. This is an easy way to get a good visual representation of important process planning information. How this is done is further explained in the coming sections of the method for Systematic Process Planning and a case study in chapter 6. The colours and their respective meanings are presented in Figure 4-3.

- Datum (in this operation) (blue)
- Requirement related to datum (yellow)
- Associated dimensions and features (pink)
- Datum surface in following operations (red)
- Surface created, treated or measured in this operation (green)

Figure 4-3 Scheme over highlighting colours and their meaning used for entities on drawings and sketches

One example of how the method for Systematic Process Planning can be put into practice is described in chapter 6 “Case study of a bevel gear pinion”. The disposition of the case study is identical to how the method is described in this chapter. Consequently, the content and numbering of each section in this chapter and the case study chapter are fully harmonized.

4.1 Analysis of the design and blank drawing



In the beginning of a process planning job, the analysis and interpretation of design data is essential. To review design data from a manufacturing point of view, the model or drawing should be considered in the following order:

- Application of the part?
- Design datums[4]?
- Requirements related to datums?
- Associated dimensions and features?
- Tolerances, tolerance chains, material and other requirements?
- Influence of blank?
- The ability to measure and verify quality?

The following sections (4.1.1- 4.1.7) explain these questions further.

When these issues are considered, the results must be noted and made available for later purposes.

4.1.1 Application of the part

The process planner needs to cooperate with the designer. In situations when there are manufacturing related reasons for changing or adjusting the design, there must be a discussion about the solution. For this discussion to be relevant, to avoid unnecessarily details and to reach agreement more quickly there is an advantage if the process planner has a good insight into how a specific part is intended to operate in the application (gearbox, axle etc.). The more knowledge the designer has

[4] Datum is a reference such as a plane or centre axis.

about manufacturing, the better the possibilities are for producing a good design to suit and utilize the manufacturing facilities. In analogy with that, the process planner can further substantiate the arguments for relevant design and/or process changes if he/she has good knowledge about the application of the part.

It is also an advantage if the process planner has good knowledge of the purpose of the part when searching for and discussing new methods with e.g. suppliers of machines and tooling systems. It is furthermore supposed that it is a motivating factor to know the context that the products will be a part of.

4.1.2 Design datums

A datum is a theoretical exact axis, surface, point etc. that forms a geometric reference to which other features on a part may be related.

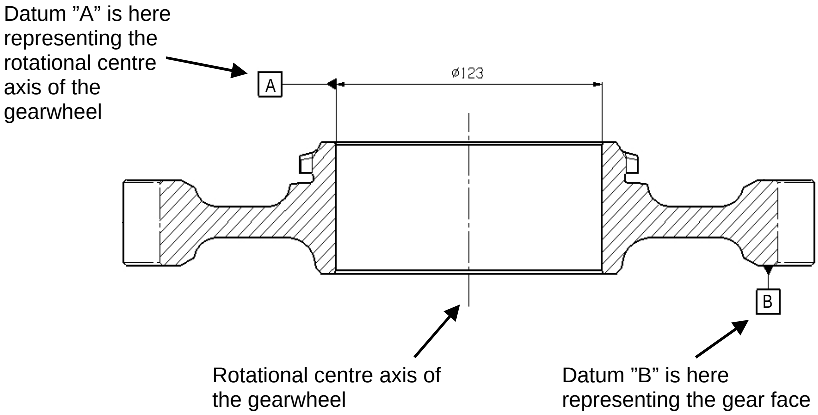


Figure 4-4 A gearwheel drawing that exemplifies how two typical datums are defined. Notation according to Svensk Standard SS-ISO 5459 (1984).

Typically, an axial line through the centre of a gearwheel or shaft is a design datum that defines the theoretical rotational axis. This is exemplified and indicated by "A" in Figure 4-4. Another datum may be the gear face, indicated by "B".

It is preferable from a design point of view to choose datums that correspond to functionality. Design dimensions and tolerances are then applied relative to the datums. This does not always result in an optimal situation for the manufacturing process because of difficulties involved in locating, clamping and measuring, but it may be necessary due to design requirements.

Datums usually have to be changed between machining operations and sometimes between last operation and final inspection. Change of datums often results in a need for re-allocating the dimensions and new calculations of tolerances (Farmer and Harris, 1984).

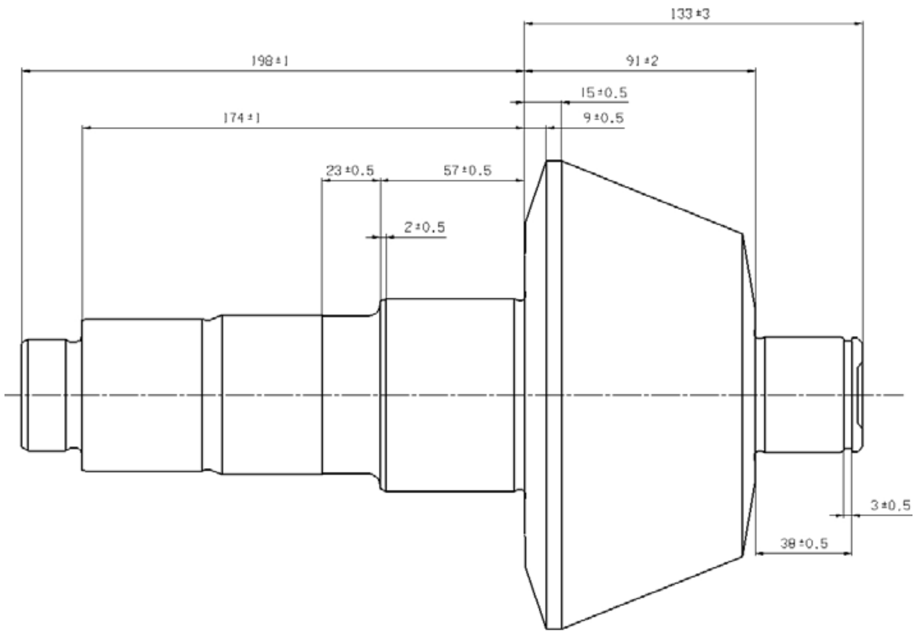


Figure 4-5 Pinion drawing with dimensions emanating from different datums.

Datums for *dimensions* are often less explicitly indicated than for geometrical tolerances. In the case of base-line dimensioning, it is obvious that the base-line represents the reference from which the dimensions are defined. Usually there is a mix of dimensions referring to a fixed datum or to other entities as seen on the pinion in Figure 4-5.

Identifying design datums on the drawing is essential for the further process planning.

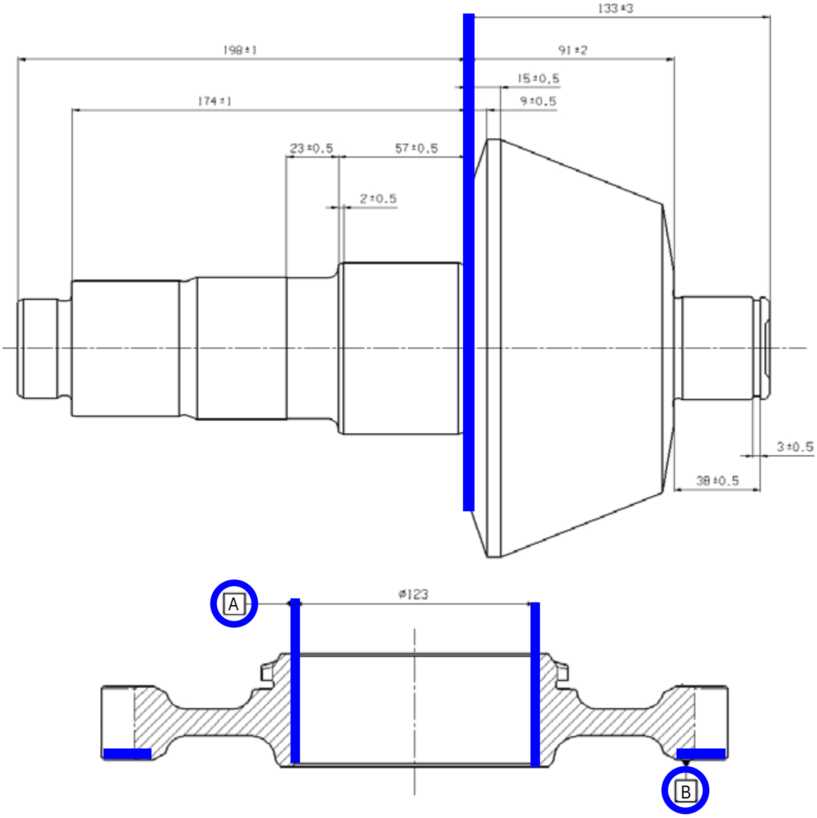


Figure 4-6 Identified design datums are marked on a pinion (above) and gearwheel drawing (below) respectively.

To visualize and get a clear view for the coming steps, mark all identified design datums on the drawing as illustrated in Figure 4-6.

4.1.3 Requirements related to datums

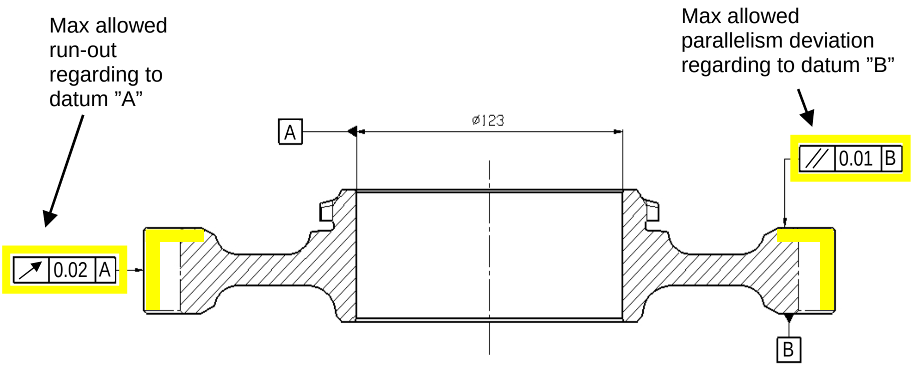


Figure 4-7 Example showing features on a gearwheel that are governed by typical geometrical requirements. A: Run-out ; B: Parallelism

As previously described, the design datums are theoretically exact references that act as bases for tolerancing the part. Typically, geometrical tolerances for orientation, location, run-out and parallelism are some examples of requirements that are related to datum references (Helevi and Weill, 1995). Figure 4-7 shows two of them; run-out and parallelism.

If a datum for *dimensions* (as described in section 4.1.2) is identified, all dimensions related to this are easy to find because they are explicitly attached to the datum (see Figure 4-6). Therefore, a *dimension* related to a datum does not need to be specifically indicated on the sketch.

Identify and yellow mark all geometrical tolerances that are related to the datums. This is exemplified in Figure 4-7.

4.1.4 Associated dimensions and features

The next step is to identify associated dimensions and features that have not already been considered as "related to datums" in the previous step.

A measure can either be seen as a dimension that defines the size or as a relative position of a certain feature. It is easy to imagine how a diametrical measure shows a size and also that the length of a slot is a size. The position of the slot is also defined by a dimension but does not give any information about the size. In this step, it is important to find how different single surfaces, features or groups of features are associated and positioned in relation to each other. See example in Figure 4-8.

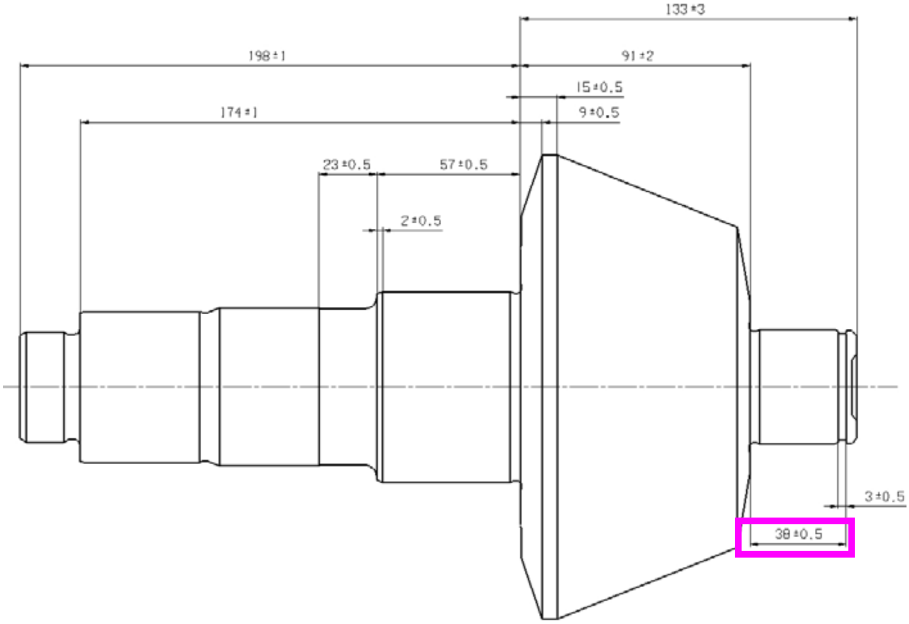


Figure 4-8 Position of a retaining ring groove is indicated on a pinion drawing.

This information will be crucial for a proper sequencing of operations without unnecessary loss of space for tolerancing. These dimensions are indicated with the colour pink, according to the colour scheme in Figure 4-3.

4.1.5 Tolerances, tolerance chains, material and other requirements

Identify all dimensional and geometrical tolerances; make notes and a first reflection over how they can be reached with known and available manufacturing methods. Also, observe the presence of tolerance chains.

Not all requirements are explicit stated on the drawing for each feature. There are often general directives for “Edges broken”, “Surface texture” or “Technical regulations” as showed in Figure 4-9.

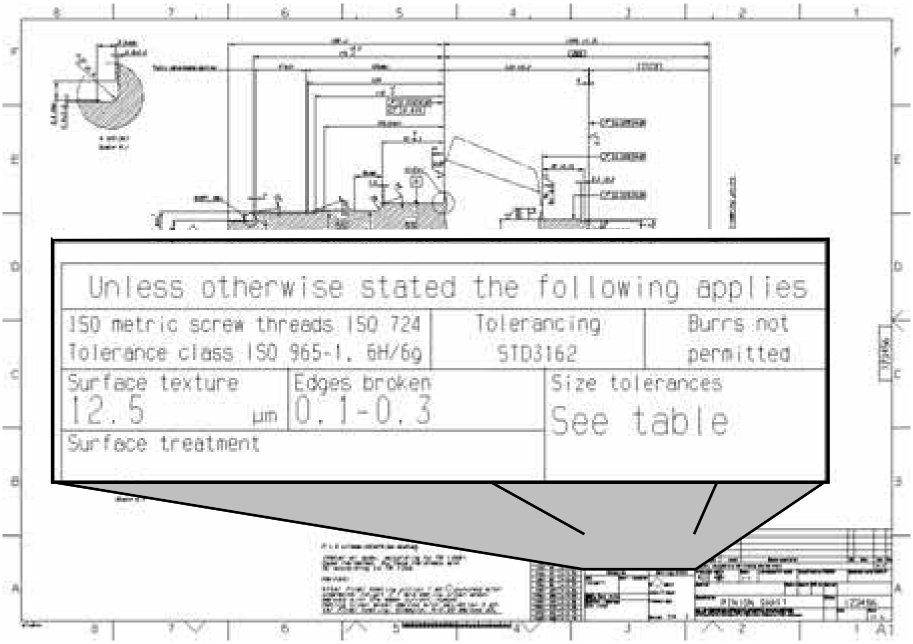


Figure 4-9 Typical general requirements shown on a pinion drawing.

Make it clear if there is any quenching, carburizing, blasting, shot peening or other treatments to be done. These are sometimes required for some specific surfaces and restricted for others.

Find out about the part's material. This information is often found on the blank drawing but may be stated on the design drawing.

In this stage, there is a good help to have data showing both the capabilities of available machining resources in the workshop and what different methods can perform in general. The latter can be found in literature concerning manufacturing methods and process planning (Helevi and Weill, 1995). With this information, it is easier to make a *first estimation* of the kind of equipment that is required for the specific task.

To get a more complete insight whether tolerances can be achieved, the process planning work must proceed through all steps in this method to cover the entire manufacturing process.

4.1.6 Influence of blank

In the case of the manufacturing of gears, shafts, pinions and crown wheels, the raw material is mainly some kind of forged steel blank. By studying Svensk Standard SS-EN 10243-1 (1999) it can be seen that a commonly used closed die-forging process gives tolerances that are approximately ten to one-hundred times wider than typical tolerances for machined surfaces in general. Examples given of tolerances for a forged pinion blank are found in Figure 4-10 below.

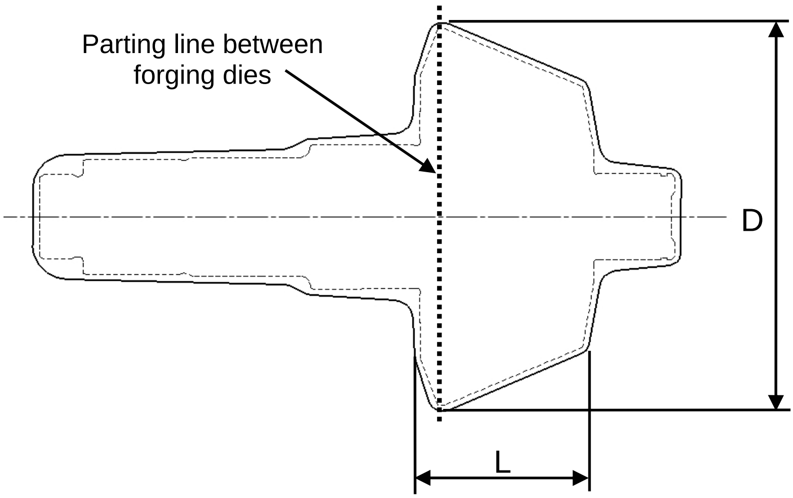


Figure 4-10 Representative tolerances for a pinion forging with a weight of approximately 25 kg:
L - ***Axial distance tolerance (between dies) +3.3/-1.7 mm***
D - ***Diametrical tolerance (∅200) +3/-1.5 mm***

However, there are many different ways to design and forge the blanks. According to Bodin (2003), there are at present methods for precision forging of gears that can give geometries near net-shape. Nevertheless, in applications that are covered in this thesis, none of the parts; gear, shaft, pinion or crown wheel, can be completely produced by a forming method. There is more or less a need for machining and treating some kind of raw material such as a forged blank.

Depending on the part function and aims of the designer, the geometry of the blank can partly represent the geometry of the finished part. This relationship depends on how much of the blank that is going to be machined.

The importance of making a good interpretation of the blank itself cannot be emphasized enough.

In general, the following points have to be examined when checking a forged blank drawing:

- Shape and position of parting line (line between dies)
- Dimensional tolerances (e.g. diameter, width, thickness)
- Machining allowances
- Mismatch – tolerance for misalignment between dies
- Tolerances for residual flash or trimmed flat
- Straightness and flatness
- Fillet and edge radii tolerances
- Draft angles and tolerances
- Burr tolerances
- Surface tolerances
- Locating positions for machining

All these items affect how the process planning is to be performed.

Positioning and clamping of a forged blank is considerably affected by the tolerances of the blank but also by how and where positioning and clamping positions are defined. As an example, it is always preferable to have small variations and uniform distribution of machining allowances (i.e. no run-out). This minimizes variations in cutting forces and unbalance due to mass distribution, which affects machining accuracy. It will also make it possible to have smaller machining allowances due to less uncertainty over whether there is enough material for a clean cut all around the part.

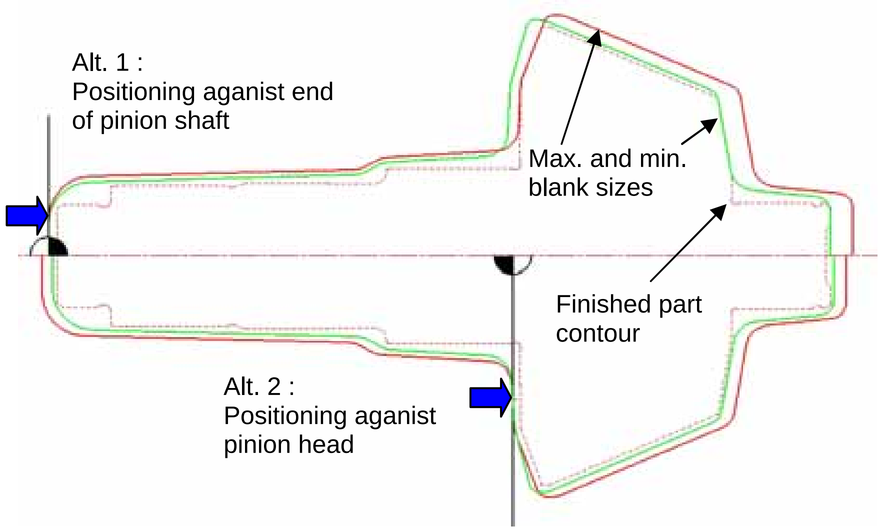


Figure 4-11 Different blank sizes and positioning points affect machining allowances. The topmost half of the drawing shows alternative 1 and the lower half shows alternative 2.

The choice of location, clamping, and machining data must be capable of taking care of all variations defined by the blank specification (see Figure 4-11). If the finished part is designed to have a geometry that is partly represented by the blank, there is at least one transition between a forged and a machined surface. See Figure 3-4 on page 22 where a gearwheel is illustrated. Due to the relatively wide tolerances on a forged blank, it must be up to the process planner and designer to minimize negative consequences. These consequences are, for example, variation of intersection positions between machined and forged surfaces, mainly due to blank variations.

4.1.7 The ability to measure and verify quality

One of the fundamentals of modern manufacturing is that it must be possible to verify that a product conforms to the desired specification. This means, that there must be a method for measuring and evaluating each property of a produced part. In the context of this thesis, the methods have to be capable of evaluating, for example, dimensional and geometrical requirements, surfaces, hardness and hardening depth. There are standards that define principles for how different properties can be measured and evaluated. One of them is Svensk Standard SS 2650

(1989). These standards do not cover all possible design solutions and have to be interpreted for every particular property of a part.

In many cases, there are different possibilities to measure but with different results depending on factors like method, choice of measuring sequence and evaluation of data. This is an important issue to observe especially when using Coordinate Measuring Machines (CMM).

a) b)

Figure 4-12 a) "Accura" Coordinate measuring machine (CMM) from Zeiss.
b) Measuring probe (DynaTouch) from Zeiss.

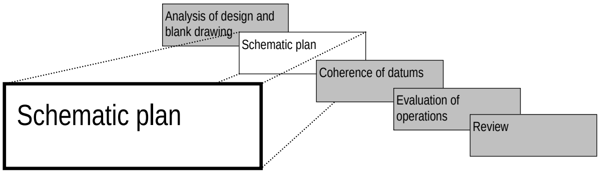
A CMM must: 1) be set up with some measuring probe, 2) set up with a fixture for the workpiece, 3) taught or programmed where to pick strategic measuring points and then 4) evaluate the measuring data in a certain way. The result is highly dependent on how these four (1-4) steps have been performed. Each step offers an extensive number of ways to choose between. This implies that the results will differ depending on the way the CMM is used.

The original methods (before the invention of CMMs) for measuring and evaluation, for example geometrical tolerances, are mainly based on a functional approach. A mandrel, surface plate, V-block etc. can be used to "simulate" datums. These simulated datums differ more or less from those used by the CMM, where the datums are estimated from a finite number of measuring points.

Designer, process planner and personnel with good knowledge in measuring technique must discuss all uncertainties regarding measuring procedures of the finished part; otherwise, the intended quality cannot be assured. Not all difficulties can be overcome by adapting the design but the consequences must be handled in some way.

The ability to measure is a task to manage, not only looking at the finished part, but also at the workpiece when passing different manufacturing operations in the process.

4.2 The schematic plan



When producing transmission parts in high volumes, the manufacturing is often performed in a couple of machine tools with different functional abilities and with different purposes. There are examples of multi-functional equipment where the complete job can be done in one machine tool, but line or cell production is more common. It is essential to look at the entire process chain when making a proper process plan for capable manufacturing. The reason is evident in the context of transmission parts, because many operations have to be combined and related to each other to achieve a part with given properties.

It is necessary to get a good overview of the complete process chain. Therefore, the schematic plan is introduced as a platform for the continuing process planning work. The primarily contribution to better process plans is that the operation sequence, relationships between operations, detailed facts, intentions, decisions etc. can be continuously visualized and documented in an uncomplicated way.

A practical approach to produce this schematic plan is to start with print out's of a schematic view of the finished part. See Figure 4-13.

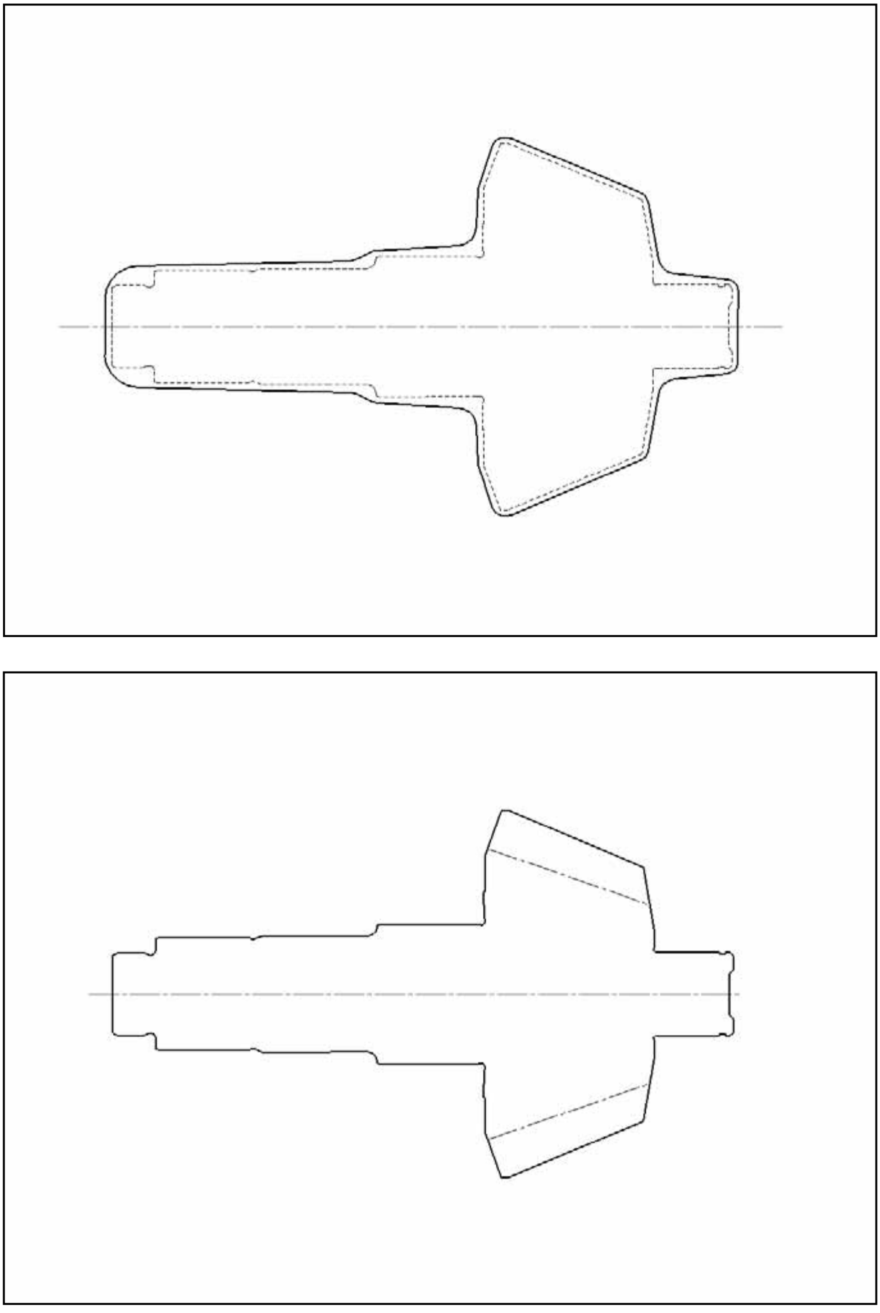


Figure 4-13 Schematic views of pinion blank (on top) and finished pinion (at the bottom). The figure symbolizes print-outs on a sheet of paper.

Paper size A4 or A3 is suitable in most cases and will allow a schematic part to be put in the centre and sketches, notes etc. are placed around. If there is a blank drawing available, a schematic view of the blank is preferably used as a complement for the first machining-operations.

The printed template illustrating the finished part will be used later on for showing relevant information about each step in the manufacturing process. It is easy to arrange all the views for the different operations in a sequence that corresponds to the intended manufacturing process.

The route from the start, with plain schematic sketches, via one or more preliminary plans, to the "final" revised and verified plan is a continuous development. Then, because of the dynamic nature of manufacturing systems where things change for different reasons, it should be used as an updatable "normal plan" during the lifecycle of a particular part.

This approach does not give recommendations on how technical issues should be solved, but will be a valuable tool as a facilitator of systematic analysis and evaluation where relevant questions are put on the table.

4.2.1 Operation sequence

Setting up a schematic plan is tackled by starting with the finished part. The manufacturing operation sequence is then defined in the reversed order until the first operation is reached.

A description of the procedure follows:

(Use colours according to the scheme in Figure 4-3 at page 29.)

1. Use a printed template and indicate design datums (blue) and related features (yellow) for the finished part. This is the same as carried out with the design drawing in section 4.1.2-4.1.3. The information is now accordingly transferred to the schematic plan.
   Write the heading (e.g. "Finished part") to indicate the status of the described part.

2. Allow the next template or templates to represent the final inspection. Use one for each measuring set-up. As in the first step, indicate all datums that will be in use for this operation. Preferably, these datums are equal to the design datums but this may not be possible in all cases.
   Also, indicate the features or surfaces that will be measured in this set-up (green). State a proper heading for each set-up template.

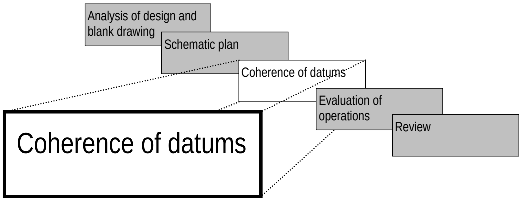
3. Continue with the last operation in the *manufacturing process*. Pick a template; indicate datums and all properties on the part that are influenced (machined, treated etc.) in this operation. Mark surfaces that will be used for measuring purposes (red).
   Make a schematic sketch of the preferred localization/clamping tool to show how this is related to the part.

4. Follow the same procedure as in step 3 for all operations backwards in the process. Also indicate surfaces that are used as datum features for any operation *later* in the *manufacturing* process (red). Extra care should be taken about these!

   In some cases there can be a reason to consider if a certain datum feature is negatively affected by the present operation. If there are uncertainties, it should be regarded and indicated as a new datum in the further process. For example, heat treatment often brings distortions to a workpiece that will change a datum feature and/or the relationships with other entities.

5. Finally, take the blank into consideration. Use a template showing the blank and indicate:
   - Locating positions (eventually stated on blank drawing)
   - Position of parting line
   - Direction of mismatch (equal to direction of die-displacement)
   - Positions for residual flash, trimmed flat and burrs

4.3 Coherence of datums



With the preliminary schematic plan described in chapter 4.2 in hand, the next step is to identify *general relationships* between operations. The very important issue in this stage is to consider and understand how datum features are chosen through the proposed operation sequence and how well they agree with the design datums.

Every change of datum implies tolerance allocation and contributes to a tolerance stack-up (Farmer and Harris, 1984; Britton 2002). At least one, or a few, changes of datum are difficult to avoid in real practice. These changes must be made with respect to negative consequences. In addition to the tolerance stack-up due to change of datum, there is an inaccuracy when changing part set-up in one single machine or between different machines.

4.3.1 Using a datum-hierarchy diagram

A procedure is now described for finding the relationships between different features and datums. Example given is to find out which datums that has been used during the manufacturing process for creating a certain feature like the gear, a face or a bearing surface. Or how the gear and the bearing surface are related to each other.

The procedure is mainly based on a graphical approach for tolerance charting used by Whybrew et al. (1990) where a “rooted-tree” is used for visualizing the links between entities of a coherence part. In later publications the tolerancing and tree technique are extended and the denomination of the rooted-tree is changed to “datum-hierarchy tree” (Thimm et al., 2001).

The rooted-tree is used in this thesis for identifying coherence of datums. In this context it is therefore logical to denominate the diagram as a datum-hierarchy diagram.

The results will clearly show:

* Operations along the way from one feature to another, where one of them may be a datum.
* Which operations (or tasks) that are performed in the same set-up/clamping

Making a datum-hierarchy diagram as described below and following the procedure to identify relationships between operations will be of great help when evaluating a process plan.

How to use this technique is also exemplified as a part of the pinion case study described in section 6.3.1 on page 90.

For each operation, first the machined surface (A, B, C etc.) and then the surface used as datum feature are put into a datum-hierarchy diagram as shown below in Figure 4-14.

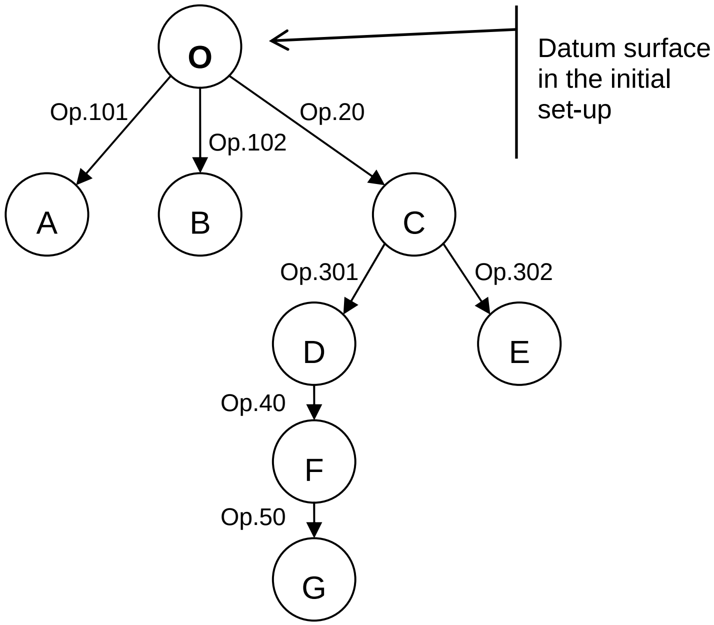


Figure 4-14 Datum-hierarchy diagram (rooted-tree) for seven operations in five set-ups/clampings.

Table 4-1 below contains a list of the corresponding machining sequence to that drawn in the diagram. Seven operations carried out in five set-ups (clampings) are described.

Features in this case typically include surfaces, centre holes etc. The operations are numbered so that is possible to read out if they are performed in the same set-up. E.g. the first two digits in "101" means *set-up* 10 which here is assumed to be in a multi functional lathe. The third digit means *machining task* 1 which can be turning. Operation "102" is performed in the same lathe and without reclamping the part. This task can, for example, be the drilling of a keyway.

Table 4-1 Machined features and datum features corresponding to the rooted-tree diagram in Figure 4-14

Operation	Datum feature in this operation	Machined feature in this operation	Path of operations
101	O	A	O→A
102	O	B	O→B
20	O	C	O→C
301	C	D	O→C→D
302	C	E	O→C→E
40	D	F	O→C→D→F
50	F	G	O→C→D→F→G

The path between machined features can be identified by following the rootlets in the datum-hierarchy diagram (Figure 4-14). Each rootlet represents *one* operation and connects a machined feature to the used datum.

Find the relationship between for example feature E and G by using Table 4-1:

Path: E = O→C→E
G = O→C→D→F→G

Comparing the path for E with path for G gives that C is the common junction.

Path: E = O→C→E
G = O→C→D→F→G

Gives the path between E and G = E→C→D→F→G

E→G represented by operations:
Op.302 + Op.301 + Op.40 + Op.50

Find the relationship between for example feature E and A by using Table 4-1:

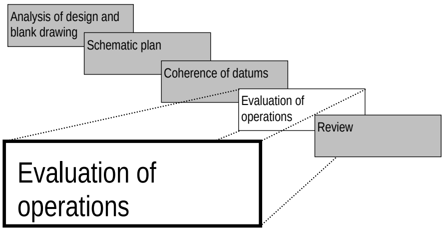
Path: E = O→C→E
A = O→A

Gives the path between E and A = E→C→O→A

E→A represented by operations:
Op.302 + Op.20 + Op.101

Tolerances are not decided, but having this information available makes it easier to avoid complicated tolerance chains and variations due to different set-ups/clampings.

4.4 Evaluation of operations



In this step consequences of the present plan will be evaluated in order to find out how well the process will work. The overall target is to get a process that behaves as expected. If this is achieved, tolerance requirements can be related to the outcome produced and a process capability can be estimated. If the capability is considered as being good enough, the process planning work can continue.

Each operation can be analysed and evaluated in order to refine knowledge about the proposed manufacturing sequence. Four main questions must always be carefully considered:

1. *What is the operation principally intended to achieve?*
   Despite this question seeming to be trivial, it is crucial to know what primarily sets the demands on each operation and what does not.

2. *How is the workpiece really machined or treated in the operation?*
   Even if the main purpose of an operation is fulfilled the part is often affected in other ways than what is explicitly described. For example, a drilled centre hole, marks from a clamping device or geometric distortions after heat treatment.

3. *What prerequisites must be fulfilled by earlier operation(s)?* Typically, this is about datum features which are created earlier in the process, or stock removal allowance (Britton et al., 2002) left for machining. It can also be related to access for cutting tools and fixtures, cleanliness, surface roughness, irregularities or geometrical deviations.
4. *Can this operation be an integral part of another operation?* Is it possible, suitable and preferable to combine the complete operation or a sub-task with another operation in the sequence?

In parallel with these four questions, there are a couple of detailed facts, highly dependant on technical constraints and choices, which must be considered. The following exemplifies these:

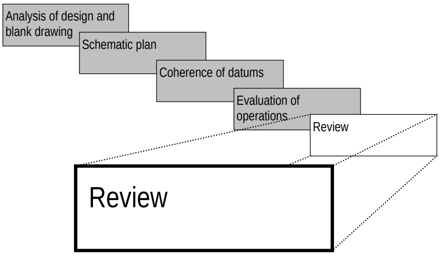
- Datums created in this operation
  How are surfaces for datum features created?
  What result can be expected?
  How are these handled due to the risk for deformation, damage, corrosion etc?
- Material conditions
  Heat treatment
  Influences from machining
  Micro structure
  Hardness
  Blasting or shot-peening
- Principles for locating- and clamping-points
  Resist excessive deflection due to machining forces (Helevi, 2003)
  Contact area between tool and workpiece
  Surface on clamping device; smooth or rough, serrated
  Prevent sliding movements of part in fixture (Helevi, 2003)

  Minimize deformation and damage due to clamping forces (Helevi, 2003)
  Clamping tools' conformity to clamping points/surfaces
  Jaws; two ,three four or more
  Collet chuck
  Centres
  Face driver

Pitch line clamping of gears
Shape of centres; interface between part and tool
Fixed centres
Rotating centres
Floating jaws
Clamping forces axial and radial
Risk for part misalignment due to chips and moisture (Helevi, 2003)

- Cutting data
  Surface roughness
  Forces; magnitudes and directions
  Deflections due to cutting forces
  Chip forming
  Cutting dynamics
- Cutting tools
  Surface roughness
  Chip forming
  Accessibility
- Environmental aspects
  Cutting oil or emulsion
  Dry machining
  Exposure to moisture, chips and pollutions
- Temperature
  How does temperature affect the operation?
  Does the operation change the temperature of the workpiece?
- Measuring
  How, what and when?
  Set-up
  Process control
- Capability
  Expected quality under current conditions.
- Part loading, unloading and transportation
  Localization
  Positioning
  Surfaces for gripping etc.
  Packing

4.5 Review



So far, the following topics have been taken into consideration:

- Analysis of the design
- Set up of a schematic process plan
- Coherence of datums
- Evaluation of operations

Very likely, there are items identified that need to be changed in the schematic process plan and on the design drawing to achieve a better process and design. If there is a necessity to adapt the design in some way to facilitate easier and more capable machining in one operation, it may affect other operations or the entire manufacturing sequence. To achieve a more capable process and still keep the functionality of the designed part, the designer may need to balance the tolerances. If one tolerance range is increased, another corresponding tolerance may be decreased which must be incorporated in the process plan.

Things that were difficult to foresee at the start, or that needed to be confirmed in the context of a better defined process, may now result in a need to change for example manufacturing sequence, type of fixture, control strategy or maximum cutting forces. This implies that new choices and decisions must be taken, the schematic process plan revised and the expected overall capability be revaluated.

5 Discussion and conclusions

This chapter includes a discussion about the topic of process planning as a consequence of the framework built in earlier chapters. Conclusions and proposals of further work is finally presented.

5.1 Discussion

There is a need for process planning activities in different situations during the lifecycle of a product or production facility.

Before the start of production of a new product in a new workshop a complete planning procedure is required. This work must include considerations of both macro and micro levels as illustrated in Figure 3-1 on page 15. *Macro* level means typically operation sequencing and relationships between operations. *Micro* level focuses on details within each operation like cutting data and tolerances (ElMaraghy, 1993).

When changing a manufacturing process for some reason, the plan must be revised and updated due to the new conditions. In this case, there is an immediate risk of making wrong decisions if the complete manufacturing process has not been considered.

It can be an extensive job if completely new resources like machines tools, tooling, measuring equipment etc. have to be used, especially if the operation sequence must be changed. There is a huge number of factors that may influence the manufacturing process. This is why process planning in general is regarded as complex.

The nature of process planning as a multifactor process, which can be tackled from different directions, in different situations and by different competencies, is managed in a simpler way by using a systematic, standardized method. This will support making process plans where the result will be more certain and differ less in the end.

The systematic method for process planning presented in this thesis does not stipulate how decisions shall be taken but it is aimed at being a tool that allows the process planner to systemize, identify and answer the right questions. If the knowledge, thinking and logics behind a plan can be described there is a good possibility of reaching higher levels of understanding.

Making a process plan as described, facilitates highlighting of the most sensitive operations due to quality but also other factors that influence process efficiency. Differences are dependent on the decisions made in each step of a coherent chain, where consequences can be overviewed, identified and more easily evaluated. If the systematic method is used, it will be much more obvious which topics there are that have to be examined and clarified. This makes it easier to give priority to the most relevant questions.

Applying algorithms can solve some problems analytically if there are sufficient data and unambiguous constraints. In practice is it not possible to collect valid data for all parameters that theoretically can affect the process. This justifies the need for putting in knowledge-based, subjective aspects to facilitate proceeding with the process planning work. The use of both analytical and knowledge-based methods is needed during process planning (Maropoulos, 1995).

The plan can be used as a master plan where intended deviations need a mandatory decision with full awareness of the consequences.

If unpredicted problems occur, the process plan stands as a foundation to more easily deduce the root cause. The origin of thoughts will be transparent.

5.1.1 Tolerances, variations and capability of the process

Tolerancing is not the main topic for this thesis but has been dealt with by other researchers in different situations (Britton, 2002; Gao, 2003; He and Gibson, 1992). The method for schematic process planning does not define how tolerances should be determined and distributed between operations but provides the possibility to overview and interpret the relationships. As described in chapter 4.3 and others, datum changes will add variations to the tolerance stack-up. Identifying these changes is an important part of the method.

When producing transmission parts there can be many different operations to be performed, each containing different features with applied tolerances. During manufacturing the variations from each operation are interacting in a way that finally must result in a part with proper quality. The properties of the finished part must correspond to the design requirements.

A detailed schematic plan facilitates the intuitive determination if variations are *dependent* or *independent*. This is presumed as being necessary for determining manufacturing tolerances in a "smart" way.

"Smart manufacturing tolerances" here is meant to be tolerances that are defined to achieve maximum overall process capability with a minimum of effort. This conception is founded on the idea that it is possible to avoid suboptimization.

If a manufacturing process *is* suboptimized, there are parts of the process that will be negatively affected. The entire process will require more effort to be capable than was gained by the suboptimization.

It is also presumed that smart tolerancing comprises the characteristics that give a robust process, insensitive to disturbances, with good capability indices for the finished part.

5.1.2 The method for Systematic Process Planning - a contribution to robust design

By widening the discussion, not just the manufacturing process shall be considered as the target for smart tolerancing. It should also contain the product design, which must be capable of reaching a defined level of performance under given circumstances.

A robust design that takes all possible variations into consideration requires much knowledge about the manufacturing process. This knowledge is primarily a responsibility for the process planner to provide during the development of a new product and/or a new manufacturing process.

This implies that it must be possible to describe the manufacturing process' impact on the product by means of variations. Variations in each operation in the process are a matter of machine tools, fixtures, measuring equipment etc. and the quality of the workpiece transferred from previous operations.

To perform this task, the process planner needs an overview of the entire process and knowledge about capabilities of all operations. The overview and facility to interpret each operation is provided by the method for Systematic Process Planning as described in this thesis.

5.1.3 Beyond transmission parts

This thesis focuses on the manufacturing of transmission parts such as gearwheels, pinions and shafts; all with some kind of gear. There are a lot of mechanical components that are in many aspects similar to the transmission parts. The geometries are often wheel, disk or shaft-like and axial/rotational symmetrical. Examples given are flywheels, pulleys and camshafts. The manufacturing of these parts is, apart from the machining of the gear, often similar to the manufacturing of transmission parts. The principles for process planning should be the same. This makes the systematic method for process planning a potential aid for a wider range of parts than just transmission parts.

5.2 Conclusion

Interpreting process planning has gained deeper insight into the topic and some comprehensive conclusions can be drawn and summarized as follows:

> *Process planning is in many aspects a complex task to deal with. The complexity is primarily due to the wide range of different influencing factors that must be handled along the route from the idea for a new product to mature production. It is a challenge to throw light on how this multitude of factors influences the process planning results. Tackling this with a systematic approach will facilitate more efficient process planning.*

The objective of this thesis was to find and develop methods that enhance the process planning of transmission parts. These should be capable of supporting the creation of evolvable master process plans with possibilities to challenge productivity and meet changing design requirements. A research question was expressed as:

"*How can process planning of transmission parts be systemized and transparently described?*"

The method for Systematic Process Planning described in this thesis corresponds with the research question as follows:

- It describes a systematic approach to interpret new as well as mature products.
- It prescribes systematically how essential design characteristics shall be transferred to the process plan.
- It points out how attention shall be paid to datums
- It guides the process planner through the evaluation of operations
- It proposes a way to document the process planning work aimed at both immediate and future needs.

5.3 Proposals for further work

5.3.1 Tolerancing

As discussed earlier in this thesis, tolerancing is not examined in more than general terms, despite the fact that it is essential when producing a process plan. In fact, tolerancing is after all handled by process planners on a daily basis. However, to take further steps towards manufacturing processes with good capabilities and robust character, methods for tolerancing must be added to complete the systematic method described in this thesis. Finding out which tolerancing methods that are available and how they can complete the systematic method for process planning is one interesting issue to proceed with.

5.3.2 Quantify performance

A process planner needs to know what quality a manufacturing method will bring to the product - independent of methods for tolerancing and testing. Such information is often informal and highly dependant on a process planner's skills and experiences and will not surely be as objective as required. Many interfaces between cutting tools, fixtures etc. and the part will be found when examining a process plan in details. All these have an impact on the result created in a certain operation. If e.g. run-out between a shaft and a centre can be quantified under given circumstances then there is an advantage to have this information as an input to the process plan. Finding accurate and usable data for this kind of manufacturing performance will help in the work of developing capable process plans corresponding to capable manufacturing processes.

5.3.3 Capability test of the process plan

To get closer to fully predictable manufacturing processes the process plans must be tested for capability. Since capability is a consequence of tolerances *and* variations in the process both must be known or at least estimated. An ideal process plan should be a 100% prediction of a manufacturing process to avoid unpleasant surprises. If i.e. machining, fixturing and measuring performance can be quantified and put into a system that corresponds with the process plan, the outcome may be theoretically tested before start of production. It is assumed that this test is to be performed using methods for continuous simulation (e.g. system dynamics simulation) and that it includes sensitivity analysis. How this can be performed with the systematic method as a base is also scope for future research.

5.3.4 Verification of quality

Design of new transmission parts is often a matter of changing older ones, bringing in new requirements and adapting the geometries to these aims. The process planning will of course correspond to the new product and therefore contain much of present, well-known, manufacturing methods with sometimes-new requirements. If a new method is introduced, the incentives are naturally great to examine, discuss and test the performance. If only small changes are made in combination with a well known method then the incentives are not so obvious. There will always be an open question to decide when and how extensively the manufacturing process shall be tested to verify expected quality and capacity.

- Is it possible to make process plans that are good enough so that the complete process does not have to be tested before the start of production?
- Is it enough to just make careful tests on some strategic products and guarantee quality for all other product variants by virtue of probability methods and a good process plan?

Answers on these questions and good methods for guaranteeing quality in an efficient way are likely to take the introduction of new products at least one step towards shorter lead times and lower costs.

PART II

6 Case study of a bevel gear pinion

This chapter describes how the method for Systematic Process Planning presented in chapter 4 can be used for a bevel gear pinion.

In this case study, not every possible detail and approach will be included and described. The aim is that the case should act as an introductory example for using the model.

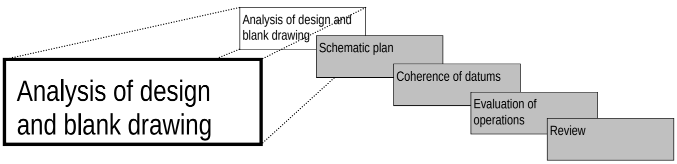
The headings and structure of this chapter are the same as chapter 4, where the method is described.

It is a condition for this case that a workshop, organization and knowledge for the manufacturing of similar products to the pinion are available. The process planning is carried out with the starting point that a new product (pinion) shall be introduced into production.

For reasons of secrecy, many of the dimensions and tolerances of the following pinion design are changed in this example. This will not affect the principles of explaining and using the method.

To show as much details as possible some of the figures with drawings are scaled to fit a whole page. This leads to a layout in this chapter where some pages are not fully utilized.

6.1 Analysis of the design and blank drawing



The pinion exemplified in this case belongs to a family of central gears with different gear ratios. The difference is the number of teeth and the design of the gear to achieve these ratios with required characteristics. This idea makes it possible to use the same design for the "shaft" for all pinions in the family. The pinion "head" is suited to fit a certain gear design. Therefore, the design is divided into two drawings (Figure 6-1 and Figure 6-2). One is for the shaft and one is for the pinion head that carries the gear.

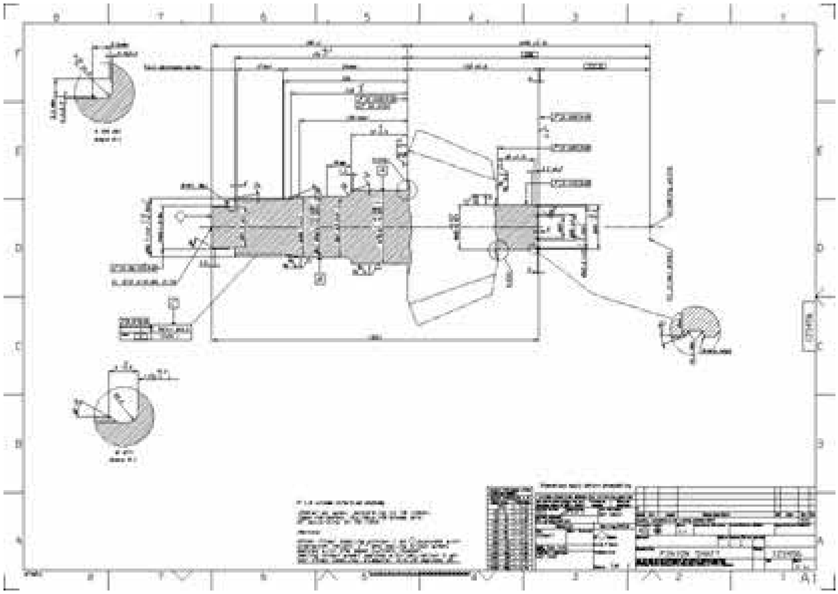


Figure 6-1 Design drawing of "Pinion shaft"

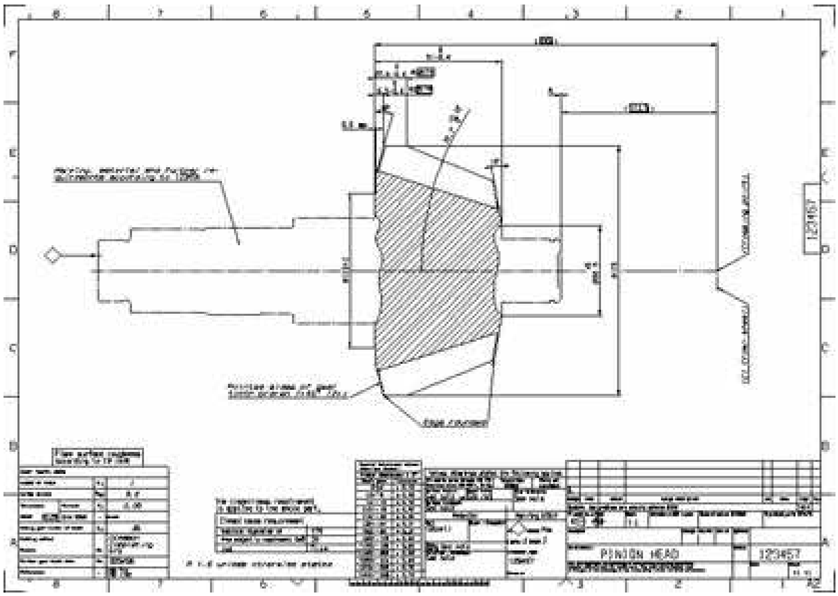


Figure 6-2 Design drawing of "Pinion head"

The procedure when analysing these two drawings will not be different from analysing a complete one. The point in this case is that the pinion head is a feature whose position is defined on the shaft drawing.

The forged pinion blank is shown below in Figure 6-3.

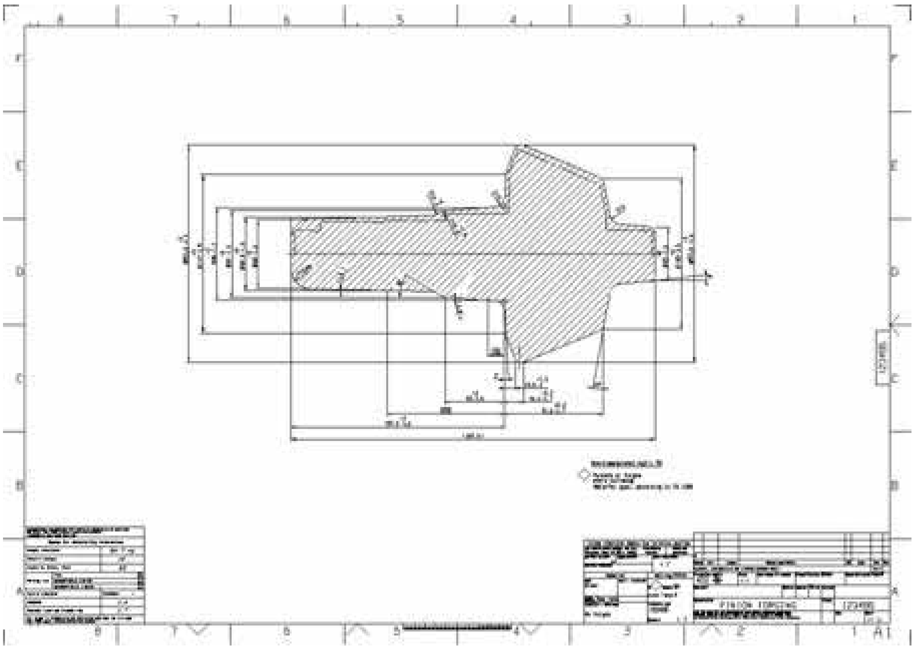


Figure 6-3 Blank drawing, "Pinion forging"

6.1.1 Application of the part

This hypoid bevel gear pinion is a part of a central gear and will be assembled with e.g. crown wheel, roller bearings, seals and differential in the rear axle of a heavy truck. An assembly drawing (Figure 6-4) shows the position of the bearings on the pinion shaft, how a nut attaches the end yoke, surfaces that are in contact with other parts, sealing surfaces etc.

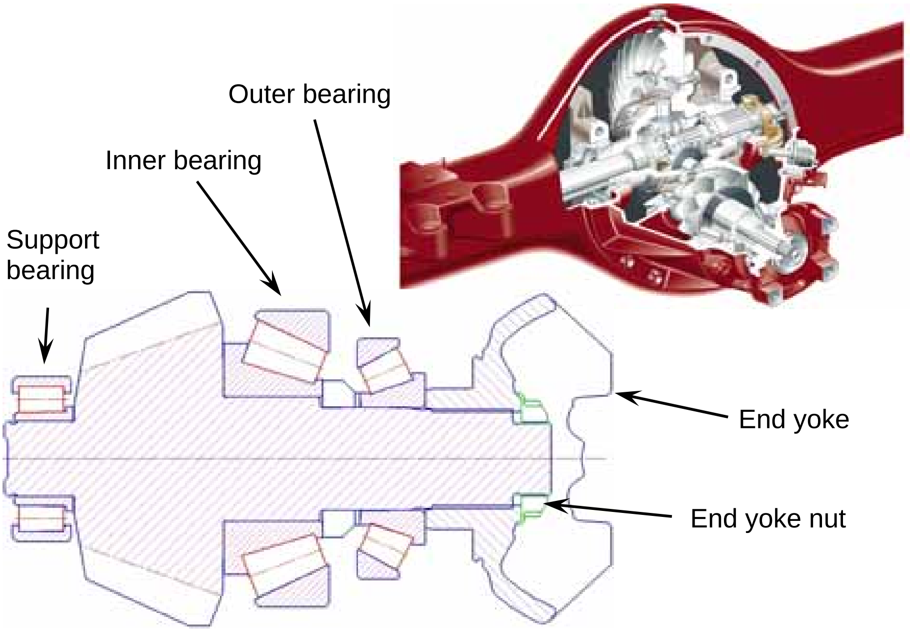


Figure 6-4 Central gear in rear axle (right) and the pinion sub-assembly (left)

6.1.2 Design datums

For geometrical tolerances, there are three datums on the design drawing which are indicated with blue colour on the drawing:

“A” – representing centre axis of the shaft diameter where inner pinion bearing will be placed.

“B” – representing centre axis of the shaft diameter where outer pinion bearing will be placed.

“C” – representing centre axis of spline for the end yoke.

The axial positioning of the pinion in the central gear housing is via the inner bearing race against the left side of the pinion head. This is the reason why most of the dimensions that define the pinion are attached to this surface, which also is indicated on the drawing. See Figure 6-5.

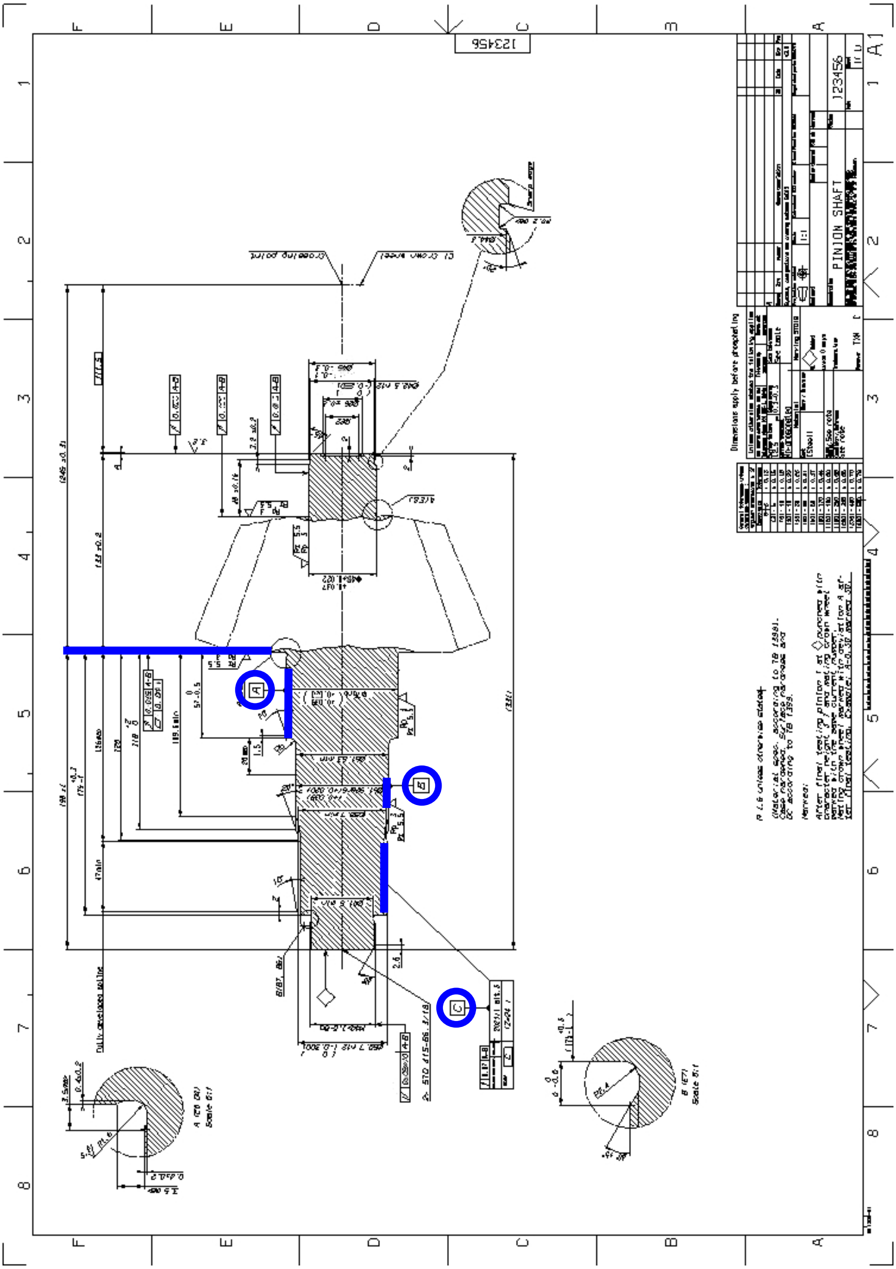


Figure 6-5 Design datums for the pinion

6.1.3 Requirements related to datums

Seven geometrical tolerances can be found on the drawing for the pinion shaft in Figure 6-6. Five of them are tolerances for axial or radial run-out. One is parallelism for the thread in the end of the shaft. The last one is for the spline where parameters other than run-out are related to the spline itself. The *pinion head drawing* shows that the bevel gear is related to datum “A-B”.

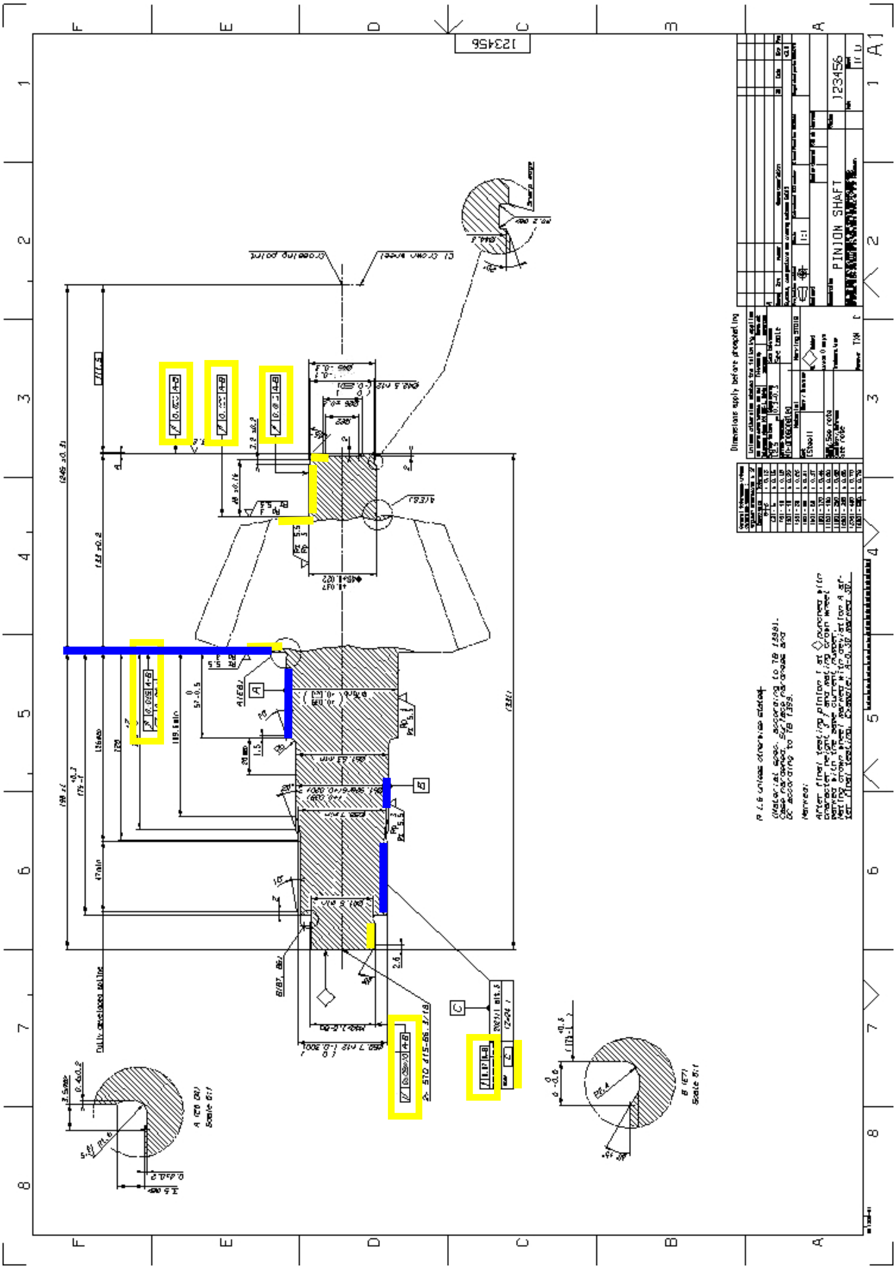


Figure 6-6 Requirements related to datums

6.1.4 Associated dimensions and features

In this step, it is important to find how different single surfaces, features or groups of features are associated and positioned in relation to each other. In this pinion case, there are for example some fillets for grinding, chamfers, the bevel gear, spline and a peg for the support bearing (see Figure 6-7). In addition, the pinion head, which is defined by a separate drawing, is a feature.

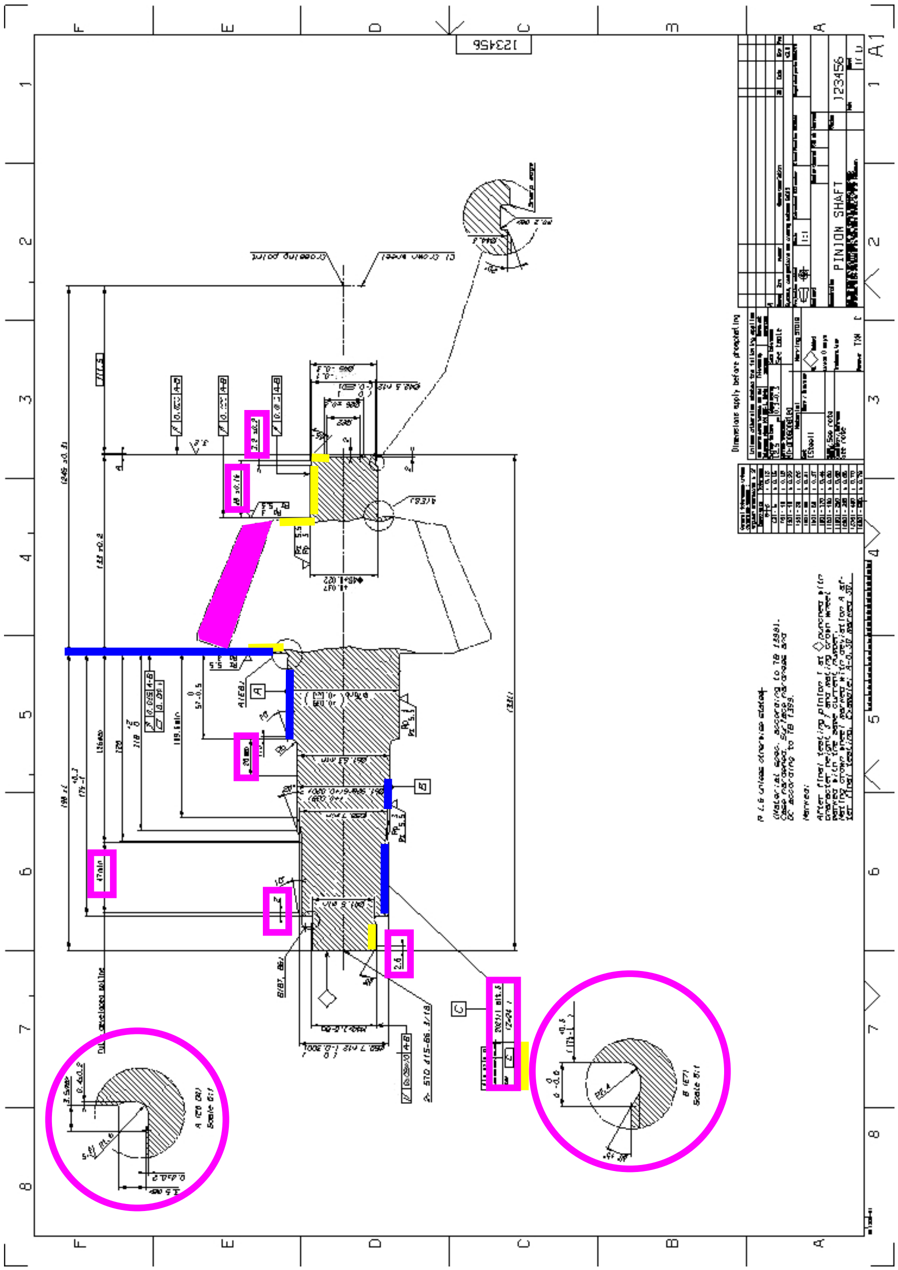


Figure 6-7 Associated dimensions

6.1.5 Tolerances, tolerance chains, material and other requirements

Now, the drawing shall be examined in detail. Identify all dimensional and geometrical tolerances; make notes and a first reflection over how they can be achieved. What has to be ground or even honed? Can turning be assumed to create the remaining features in a capable way?

In this case there are some diameters and faces that require grinding. Examples given are diameters for inner, outer and support bearings. Also, supporting faces for bearing races on both pinion shaft and support peg need grinding. There may be a potential for using hard turning instead of grinding but this method is not available in the present workshop. This idea is annotated for future use.

Workpiece material is stated on the drawing of the forged blank.

Examples of other issues found on the two pinion drawings (shaft and head):

- Case hardening treatment. (Surface hardness and depth according to technical regulations.)
- Phosphating treatment
- Edges broken 0.1-0.3

6.1.6 Influence of blank

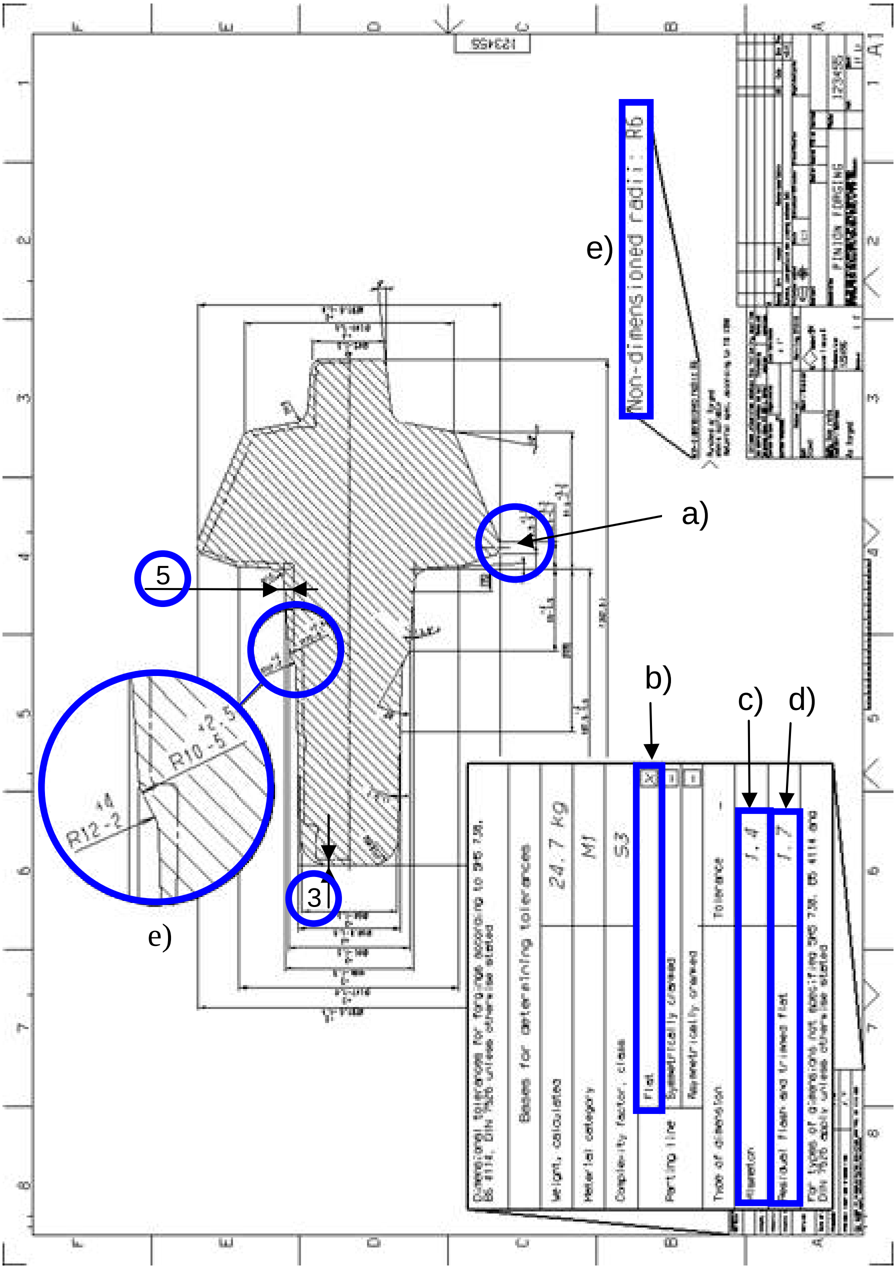


Figure 6-8 Examples of issues identified on the blank drawing.

The steel blank is made according to the blank drawing by conventional die forging methods. Unless otherwise stated on the drawing, dimensional tolerances are according to standards SMS 738, BS 4114 and DIN 7526.

Examination of the blank drawing on the basis of the check points presented earlier in chapter 4.1.6 will give good information about the blank. In this case, the blank will be completely machined. How well it is suited for the purpose will be further investigated when looking more closely at the circumstances for the first machining operations. Comments (a, b, c, d and e) referring to the blank drawing in Figure 6-8.

- Shape and position of parting line.
  a) indicates parting line position and b) that it is “flat”
- Dimensional tolerances (e.g. diameter, width, thickness).
  Typically, dimensional tolerances are +3/-1.5 mm, which corresponds to standards for this kind of part.
- Machining allowances.
  Approximately, machining allowances are 3-5 mm when the blank has the nominal size. In fillets, it is more due to big radii’s.
  When blank dimensions are at max respectively min tolerances, the allowances will in general be 1-8 mm if positioning at the pinion head. See also Figure 4-11 in chapter 4.1.6.
- Mismatch – tolerance for misalignment between dies.
  c) 1.4 mm - Will add variations in machining allowances and unbalanced weight during rough turning.
- Tolerances for residual flash or trimmed flat.
  d) 1.7 mm – at parting line.
- Straightness and flatness.
  Not applicable to this kind of part
- Fillet and edge radii tolerances.
  e) R6 in general but at some positions stated as example
  “R12+4/-2”, “R10 +2.5/-5”
- Draft angles and tolerances.
  Minimum 1.5° up to 10° with tolerance +/-1°

- Burr tolerances.
  "Burrs not permitted"
- Surface tolerances.
  Corresponding to standards.

6.1.7 The ability to measure and verify quality

Two examples are described here, which require extra attention because of practical reservations.

The first is about measuring and evaluating the conical features of the pinion head. As will be seen in Figure 6-9 below, there are two intersections whose positions are defined as a length with tolerance measured at a theoretical fix diameter of 179 mm. The drawing also states that the diameter of the pinion head is permitted to be 179 0/-0.5 mm. This implies that the theoretical intersection will not coincide with the real intersection, unless the diameter is exactly 179 mm. If the diameter is less than 179 mm, the theoretical intersection will be positioned apart from the pinion surface.

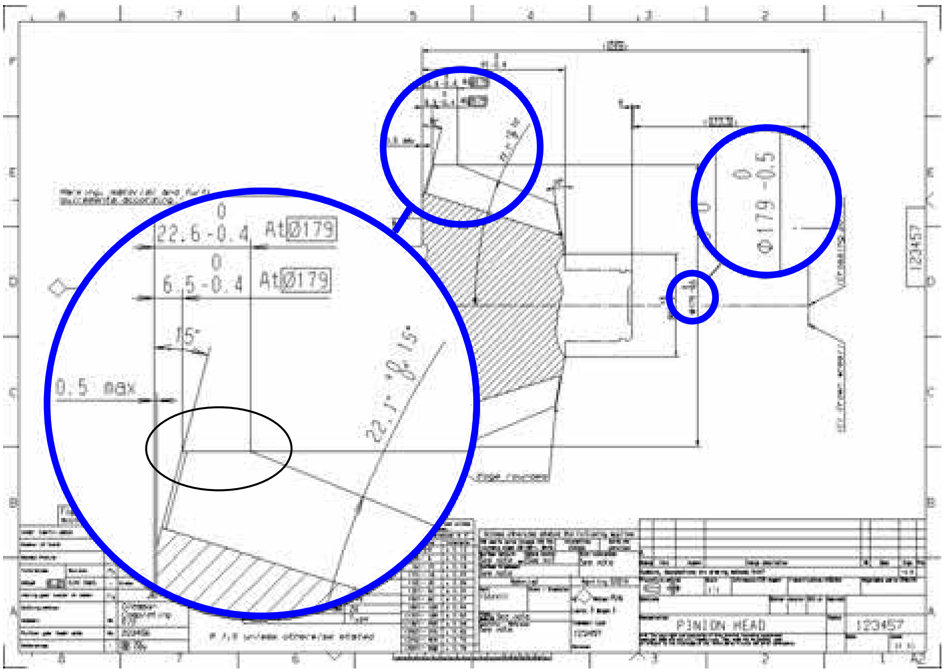


Figure 6-9 Evaluation of intersections is required

This can be measured and evaluated by a CMM, which extrapolates the contour of the pinion head to ∅179 mm and then calculates the position of the intersection. This is not very easy when using conventional gauges or height measuring instruments without changing datums and recalculating tolerances.

The second example considers another kind of situation that may be problematic due to restricted space for a measuring probe or stylus. In addition, the available measuring length has to be attended to. The fillet showed in Figure 6-10, shall be measured and evaluated due to the radius (R1.6) and surface property (Ra 3.2).

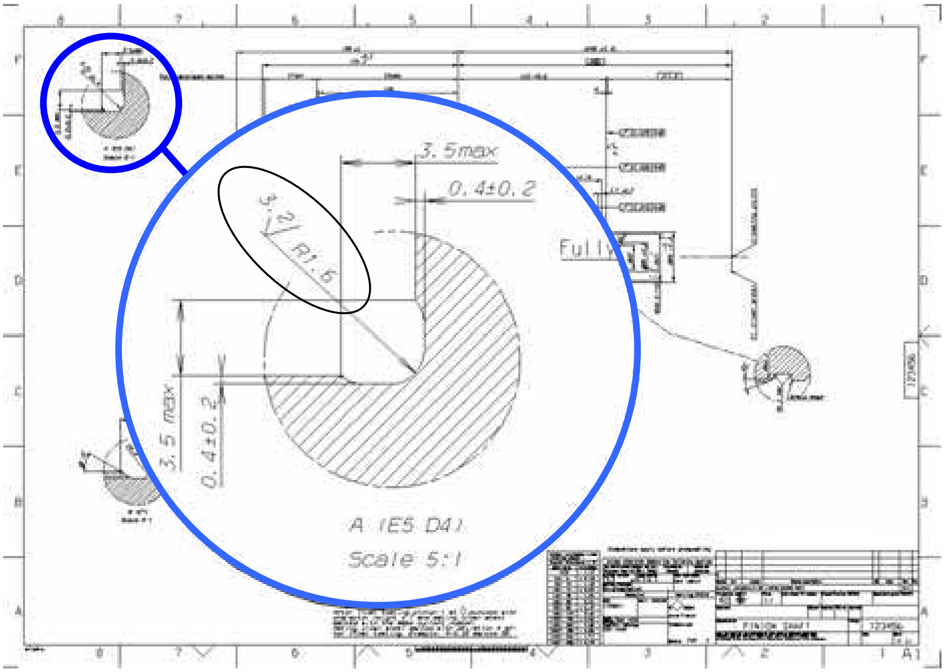
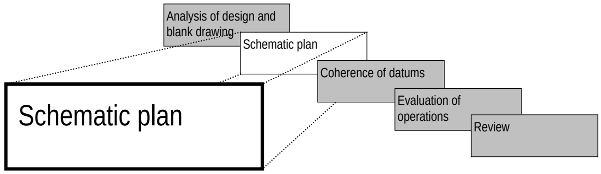


Figure 6-10 Measuring of Ra in a narrow space

6.2 The schematic plan



When the design drawings are reviewed with process planning aspects in mind, the next step is to start building up the process plan. The approach for this is to use sketches and the procedure described in chapter 4.2 which shows the geometry of the finished pinion. The contour of the pinion geometry is printed in several copies on plain paper (A4 or A3). See Figure 6-11 below. Colours are further used on it according to the colour scheme in Figure 4-3 on page 29.

For the sake of clarity, the templates presented in this example are digital and more suited for a report than the proposed printouts. In practice, the printouts are preferable due to much more flexibility and fitness for use.

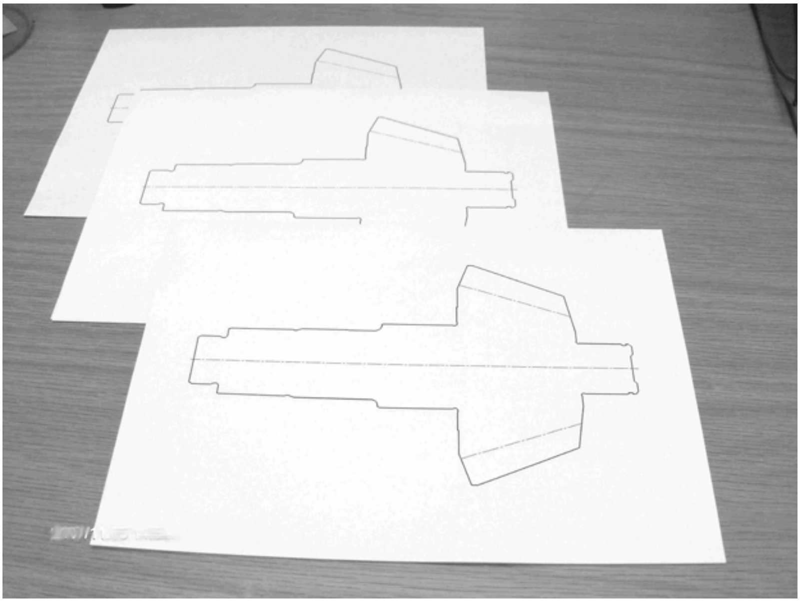


Figure 6-11 Sketches of the finished pinion

6.2.1 Operation sequence

Finished part

First, the finished part shall be visualized by means of datums and related features, in practice a transfer of information from the design drawings to the sketch. Indicate datums with blue and related features with yellow as shown in Figure 6-12.

The centre holes will be used as datum features for machining and are indicated as a and b even though they are not defined on the drawing.

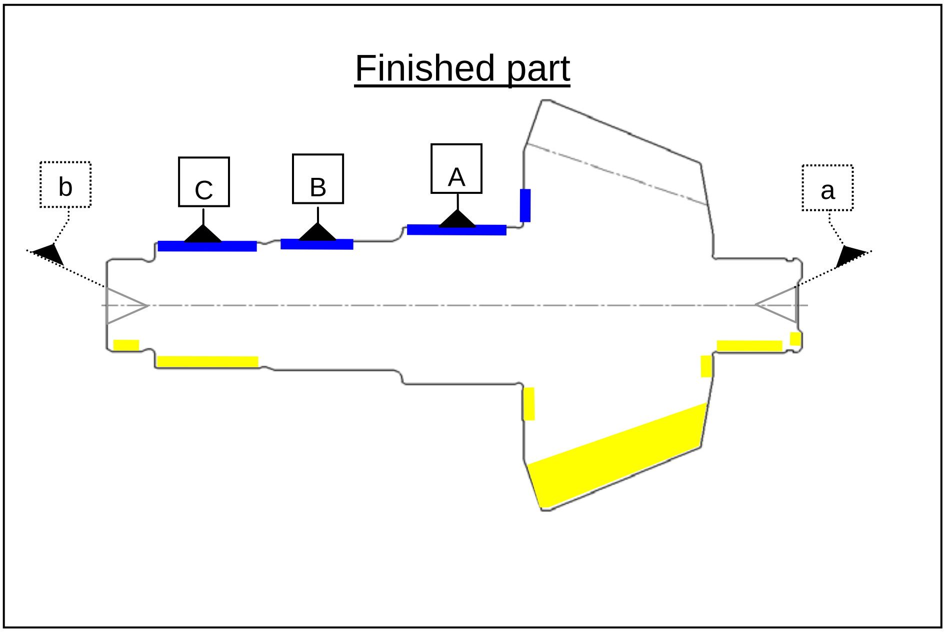


Figure 6-12 Design datums and associated features indicated on the sketch

Phosphating

Normally the next sketch should show the measuring set-up. In this case there is phosphating treatment to be carried out *after* measuring as stated on the design drawing. Consequently, the sketch with information about the phosphating operation is placed here.

The phosphating is applied to the entire pinion and is therefore indicated in green as showed in Figure 6-13.

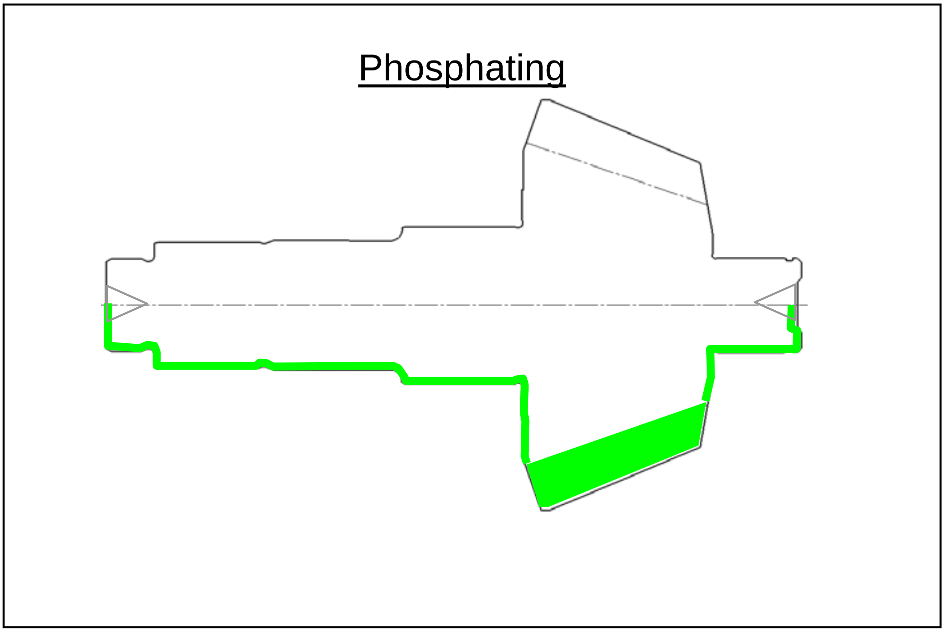


Figure 6-13 Phosphating treatment, applied after measuring due to design requirements

Measuring

The pinion is measured in two different set-ups, with two different measuring equipments. One specific measuring machine intended for gear and spline, and one CMM (Coordinate Measuring Machine) for geometries in general.

Gear measuring is carried out with respect to datums indicated in Figure 6-14, but the pinion is clamped between centres.

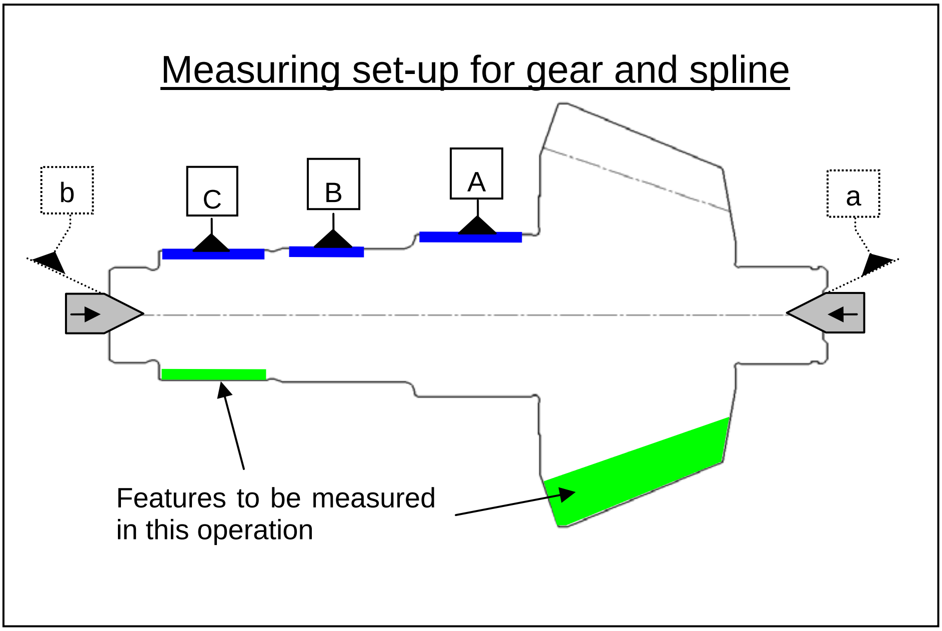


Figure 6-14 Measuring set-up for gear and spline

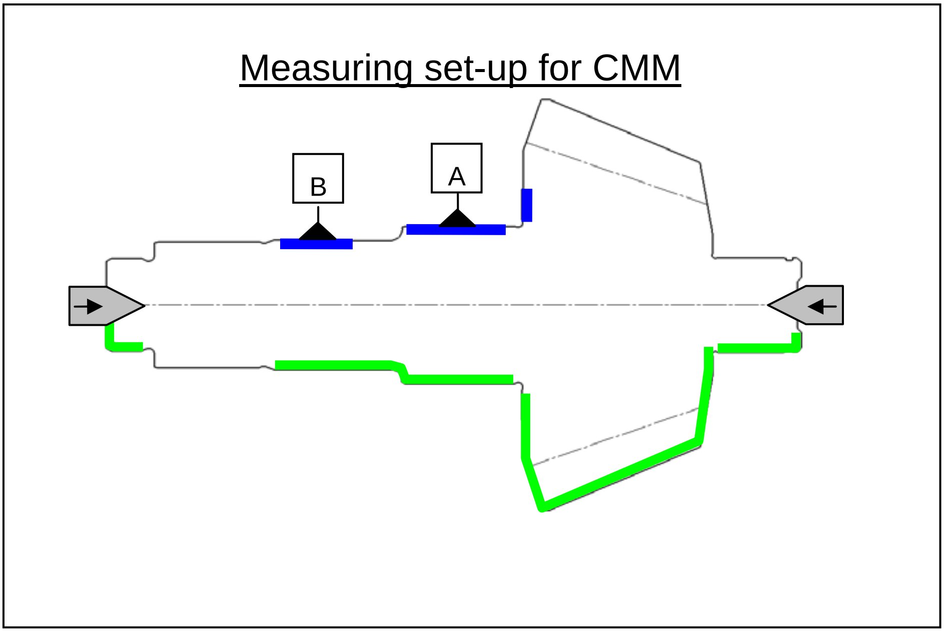


Figure 6-15 Measuring set-up for the CMM

Lapping and testing

Lapping of the gear is the final machining operation where the pinion gear and the crown wheel gear are mated and adapted to each other. The contact between gear teeth is finished and then checked by a contact pattern test. The set-up in the lapping machine is equal to the set-up in the testing machine and shown in Figure 6-16.

Clamping and positioning is performed by two collets and one stop plate. The collets centre and clamp the shaft and pull the pinion head against the stop plate for axial positioning. The aim of this set-up is to be analogous to the way that pinion and crown wheel are arranged in the central gear housing.

Centre holes are not used in this, but in later operations.

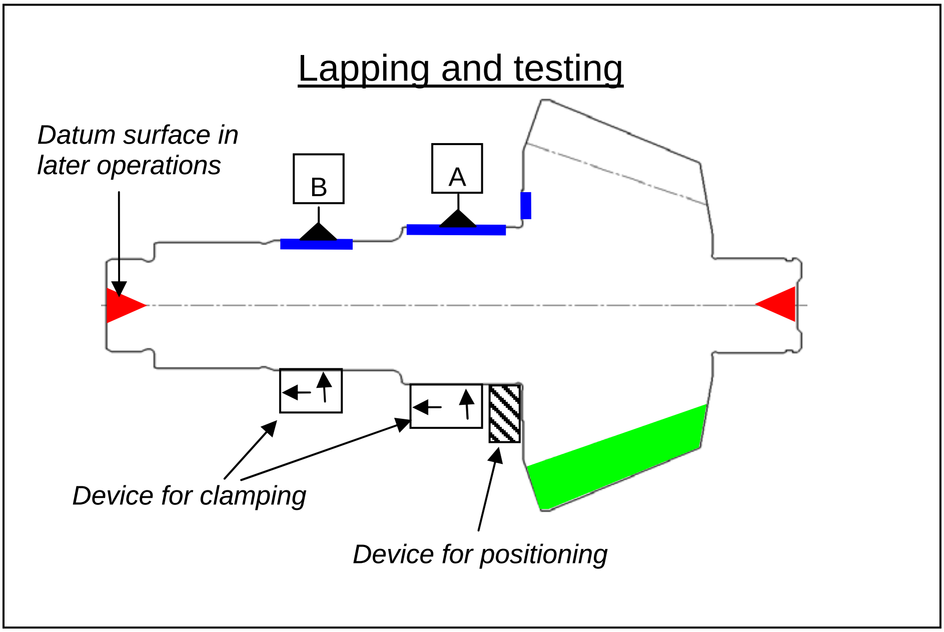


Figure 6-16   Lapping and testing of the bevel gear

Grinding

The grinding operation creates surfaces intended for bearing races. Position “2” on the left hand of the head in Figure 6-17 below, will contain the main datums for the finished pinion, which are also used for lapping, testing and measuring.

During grinding the workpiece is positioned between centres. Two different drivers are needed to avoid interference between grinding wheel and driver, but only one is used at a time. The drivers make it possible to rotate the pinion while machining. When grinding position “1”, there is a driver engaged in the spline. Engaging driver “2” in the gear enables the grinding of position “2” at the shaft and left-hand of the head.

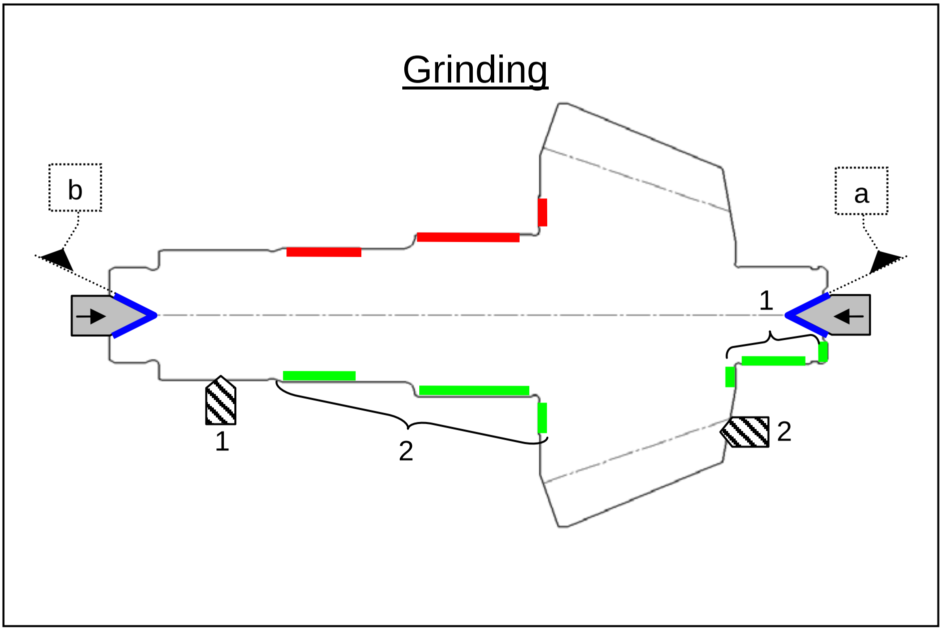


Figure 6-17 Grinding of shaft, peg and pinion head

Case hardening and tempering

The pinion is case hardened in a pusher furnace and then tempered to achieve the required surface hardness, hardening depth and material structure. The complete pinion is affected by the hardening and tempering, but not necessarily equally distributed.

There are no certain datums used in this operation. During the heat treatment the pinion is placed vertically on a tray with head downwards. The supporting surface is indicated in Figure 6-18.

However a’ and b’ are indicated as new datums for the reason described in section 4.2.1. The case hardening is assumed to distort the pinion so that the centre hole datums for the finished part (a and b) must be distinguished from the centre hole datums of the unhardened part.

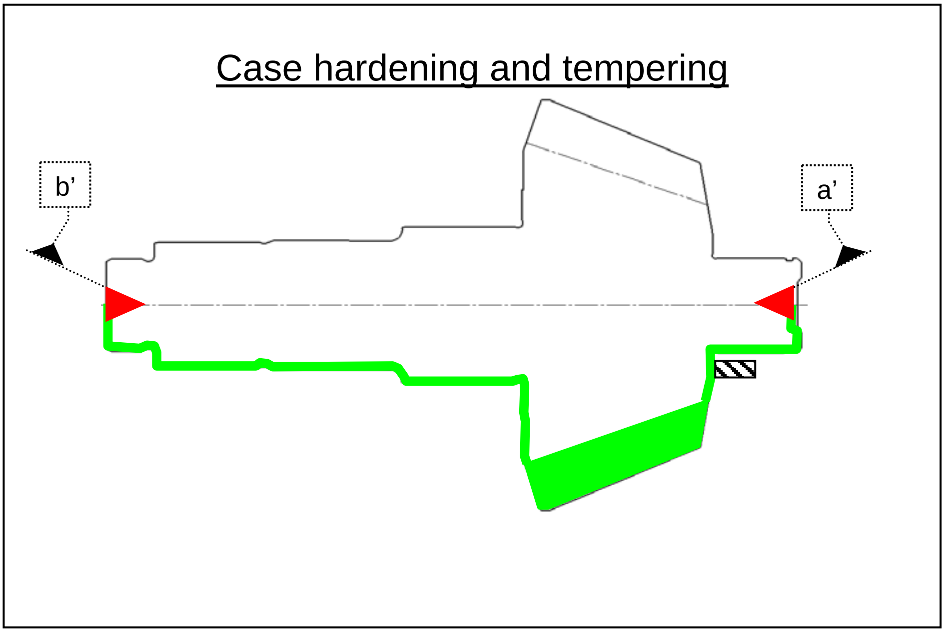


Figure 6-18 Case hardening and tempering of the pinion

Spline hobbing

The spline for this purpose is commonly cold rolled or cut by a hobbing operation. In this pinion's case, the process for hobbing is chosen due to workshop resources. If it is very likely that the chosen method in the future will be changed to cold rolling, or just alternated, this should be considered in this stage. This leads to the need for an alternative template which shows the cold rolling process´ characteristics. In this example it is not required.

The datum for spline hobbing is the axis between centres. The workpiece is axially positioned, centred and clamped between centres as illustrated in Figure 6-19. In addition, a collet chuck clamps radially at the support-bearing peg for driving purposes. The collet chuck is pulling the workpiece slightly against the right centre to avoid run-out.

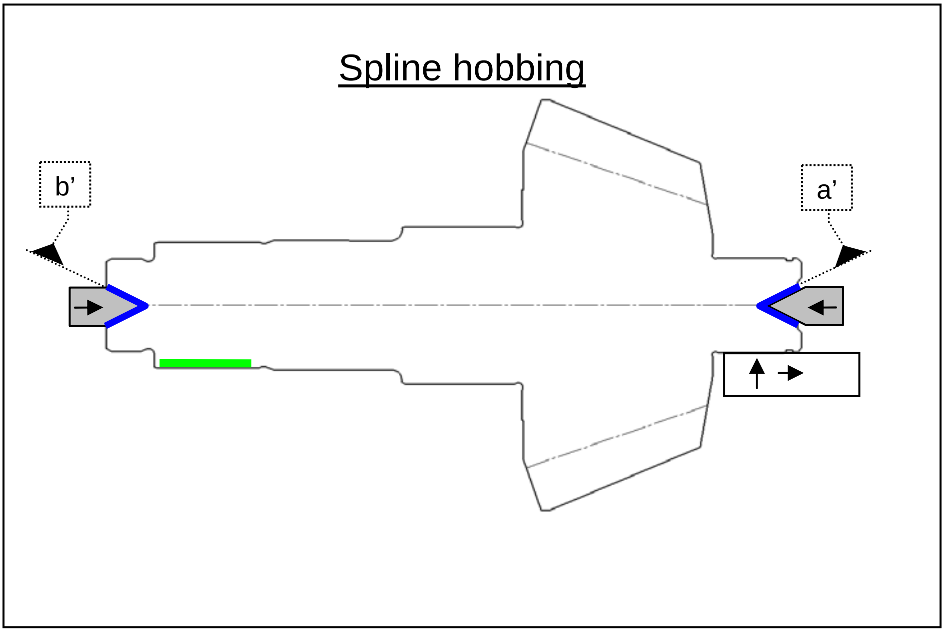


Figure 6-19 Hobbing of splines on pinion shaft

Bevel gear testing

To produce a pinion gear that will match the crown wheel gear in a correct way, the pinion must be tested against a master gear. This test is not performed on all parts in a batch, but is described here as an important operation in the manufacturing sequence which must not be neglected.

The workpiece is positioned and clamped with the same type of fixture and on the same datum surfaces as in the gear cutting operation. The datums are shown in Figure 6-20 and here named with a prim like A', to distinguish them from the main datums of the *finished* part which are ground and do <u>*not*</u> represent the same properties.

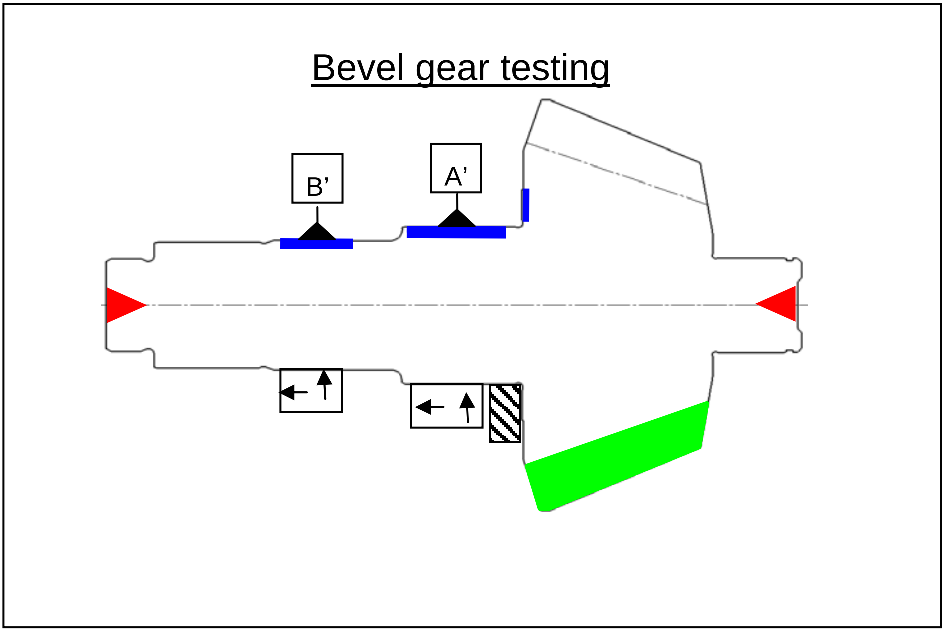


Figure 6-20 Set-up for bevel gear testing

Bevel gear cutting

The pinion has a generated bevel gear, which is cut by the single indexing method "face milling" (Stadtfeld, 2000).

A one-piece collet and a stop plate do the clamping and positioning as indicated in Figure 6-21. The collet centres and clamps the shaft on two diameters (A' and B') and simultaneously pulls the pinion head against the stop plate for axial positioning.

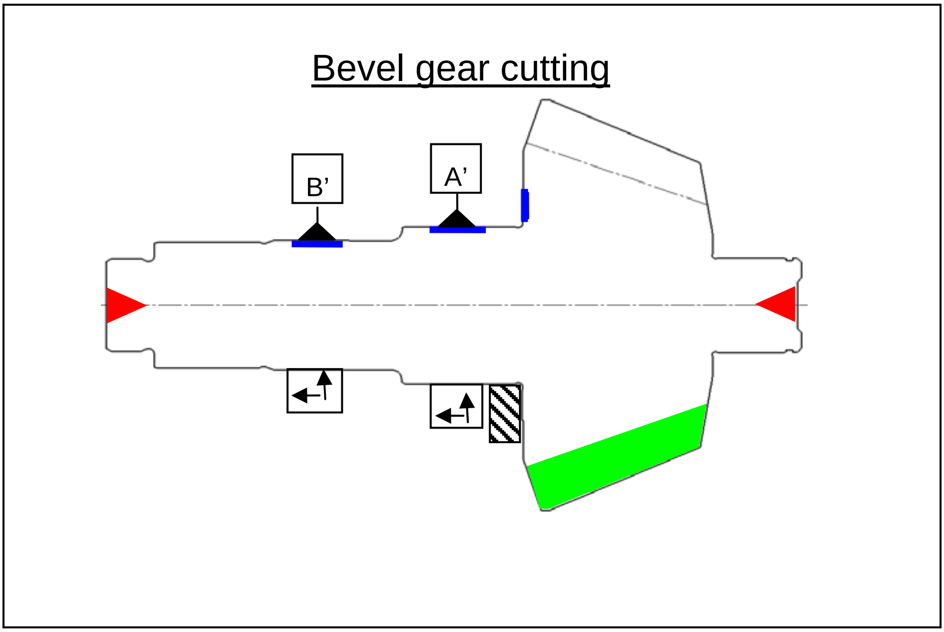


Figure 6-21 Set-up for bevel gear cutting

Turning

Apart from the centres, end faces, gear and spline the pinion is completely turned in this operation to a shape closely resembling the finished part.

New datums (A’ and B’) that will be used for the gear cutting are created from a’ and b’ (see Figure 6-22).

It may be helpful to use a template also showing the contour of the blank (like in Figure 6-23) as a complement for this operation.

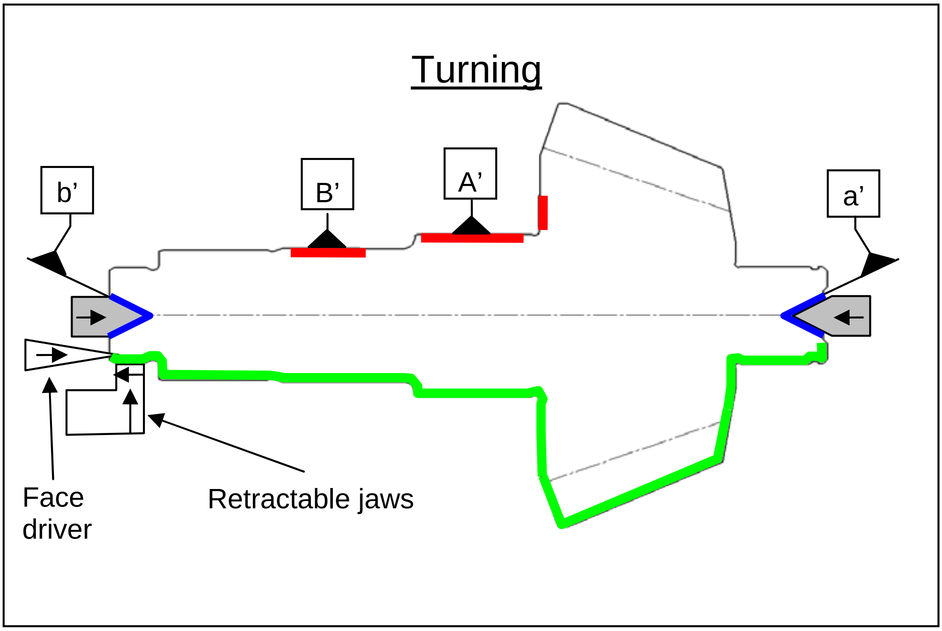


Figure 6-22 Rough and finish turning

End-machining and centre drilling

The purpose of this operation is to prepare the blank for further machining by setting the right length of the pinion and drill the centre holes.

The proposal is to clamp the blank in two positions, one on each side of the parting line. This is to equalize the run-out due to mismatch between the forging dies.

The blank is centred on two diameters by V-shaped jaws and positioned axially by a fixed stop against the pinion head. See Figure 6-23.

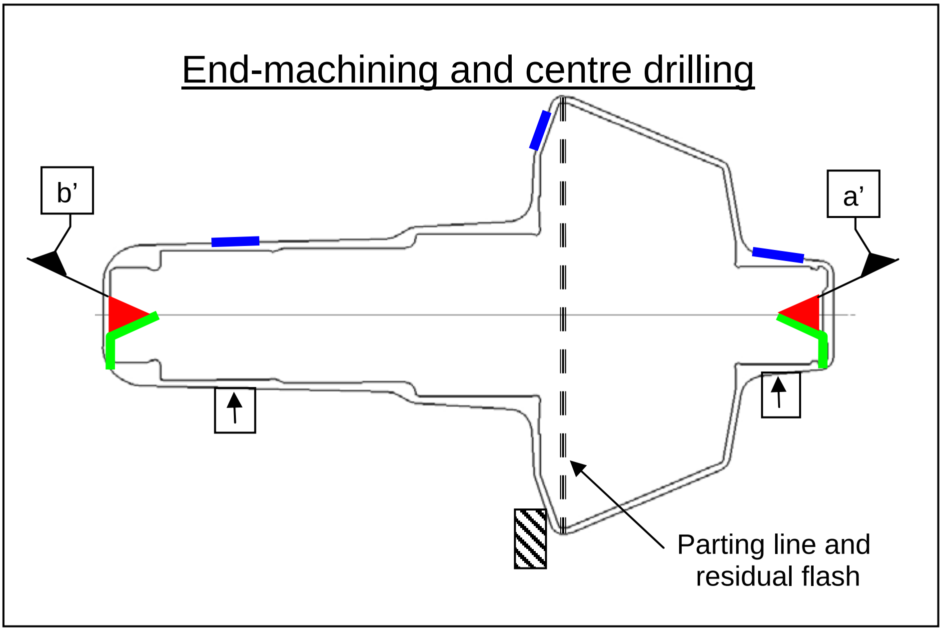
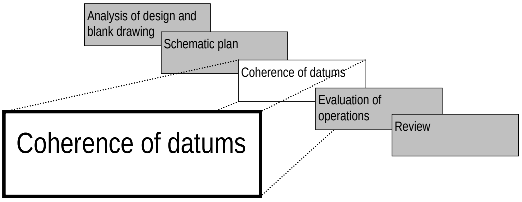


Figure 6-23 Preparation of blank; end-machining and drilling

6.3 Coherence of datums



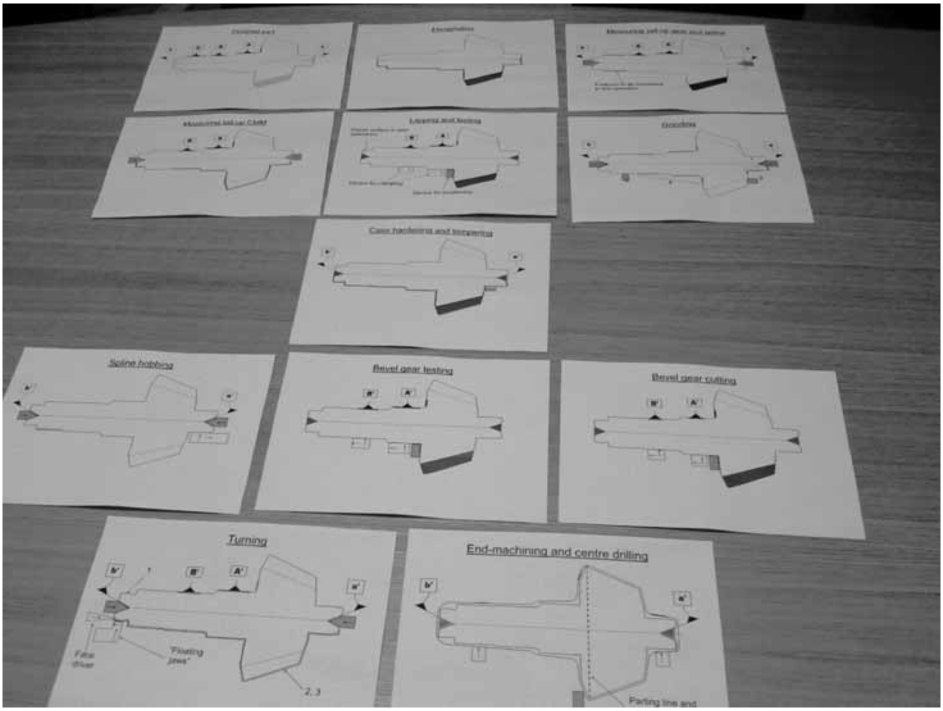


Figure 6-24 Schematic sketches of each manufacturing operation arranged in sequence for visualization purposes.

The schematic sketches that now have been created is preferable put together to form an overview of the process plan so far (see Figure 6-24).

Indication of datums and machined geometries for each operation now makes it possible to find out how the datums are used during the manufacturing process. As described in previous chapters, every change of datum to a new surface adds variations to the tolerance stack-up.

In the presented operation sequence for the pinion, a couple of datum changes can be identified. To get a clear view of these changes and cover up the entire process a datum-hierarchy diagram is established for the pinion.

The aim of the procedure presented in section 4.3.1 is to find the way through all manufacturing steps that link a feature (to which a requirement is applied) to the present datum. This procedure is implemented for the pinion in the following section.

6.3.1 Using a datum-hierarchy diagram

Templates and the proposed operation sequence created in chapter 6.2 will now be used as input to the datum-hierarchy diagram for representation and to find the relationships between datums and features.

Operations and features for the pinion are illustrated in the diagram as shown in Figure 6-25 on page 91.

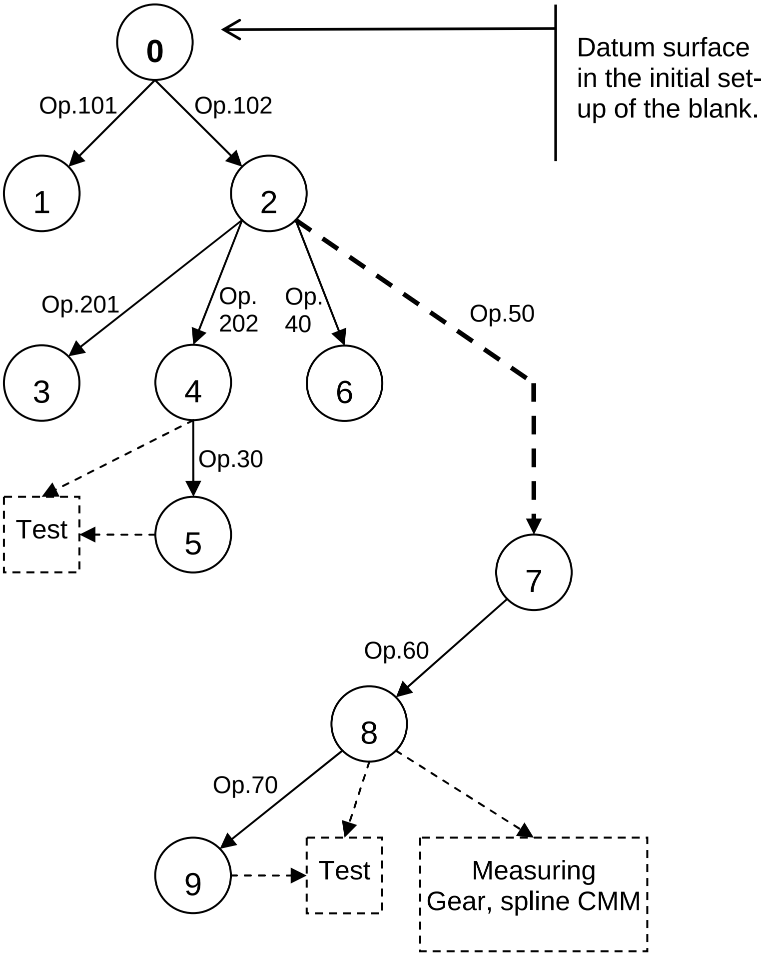


Figure 6-25 Datum-hierarchy diagram (rooted-tree) showing operations used in the pinion case.

The path between machined features can be identified by following the rootlets in the system. Each rootlet represents one operation and connects a machined feature to the used datum.

The sequence of operations and paths, including measuring, is also shown in Table 6-1.

Table 6-1 Machined features and datum features corresponding to the rooted-tree diagram in Figure 6-25.

Operation	Machined feature in this operation	Datum feature in this operation	Path of operations
101 End machining	1	0	0→1
102 Centre hole drilling	2 [a’-b’]	0	0→2
201*) Rough turning	3	*2* *[a’-b’]*	0→2→3
202 Fine turning	4 [A’-B’]	2 [a’-b’]	0→2→4
30 Bevel gear cutting	5	4 [A’-B’]	0→2→4→5
Bevel gear testing/ measuring	*(5)*	*4* [A’-B’]	*0→2→4*
40 Spline hobbing	6	2 [a’-b’]	0→2→6
50 Case-hardening	7 [a –b]	2	0→2→7
60 Grinding	8 [A –B]	7 [a –b]	0→2→7→8
70 Lapping of gear	9	8 [A –B]	0→2→7→8→9
Gear testing	*(9)*	*8* [A –B]	*0→2→7→8*
Measuring of gear and spline	*(5/9 and 6)*	*8* [A –B]	*0→2→7→8*
Measuring CMM	*(4)*	*8* [A –B]	*0→2→7→8*

*) Operation 201 is initially using datum 2 [a’-b’] (centre holes) but then also using jaws which may lead to a displacement of the datum. In cases where a roughly turned surface is used as datum will this be of importance.

In this example is the relationship between the gear and the datum A-B of the finished part to be evaluated.

Find the relationship between feature “gear” and datum A-B:

The gear[5] is cut in operation 30 and is identified as feature number 5. Datum A-B is ground in operation 60 and has feature number 8.

Path for the gear: 5 = 0→2→4→5

Path for [A-B]: 8 = 0→2→7→8

Comparing path for the gear with path for [A-B] gives that datum 2 is the common denominator.

Path: 5 = 0→2→4→5
8 = 0→2→7→8

Gives the path between gear and [A-B] = 5→4→2→7→8

Performed by the operations:

Op.30	Bevel gear cutting
Op.202	Fine turning
Op.50	Case hardening
Op.60	Grinding

Making the datum-hierarchy diagram as described gives information about the operations which will influence the quality of the gear.

Discussion about the outcome of the datum-hierarchy diagram

The following discussion is regarding to the operation sequence diagram in Figure 6-25 on page 91, starting at the top where the blank is initially clamped for end machining and centre hole drilling.

In this initial operation the forged blank will be positioned, both axially and concentrically, in relation to a common axis between the two centres. The accuracy of this blank-positioning will at least affect the machining

[5] *To make a clear explanation of the procedure in this example, one aspect of the manufacturing of the pinion was overlooked:*
Lapping operation is regarded as not changing the origin datum for the gear to A-B. The reason is that lapping, despite it being a machining process, just slightly affects the gear parameters, except for the contact pattern between pinion and crown wheel. The origin datum from gear cutting is considered to remain.

allowances in the turning process. Also, bear in mind that the blank dimensions are allowed to vary as discussed in section 6.1.6. It is not excluded that varying material properties due to uneven distribution of stock will cause problems in the process later on, for example the ability to cut or harden the material.

The first change of datum is between the centre-hole drilling (Op.102) and turning (Op.201/202). This is not regarded as a problem because the main (root) datum for the coming operations consists of the centre holes (feature number 2).

It is important to notice that the centre holes comprise the common denominator from where both the gear and the datum A-B have their origin. This implies the need for making good quality centre holes and using appropriate tools for positioning in these holes.

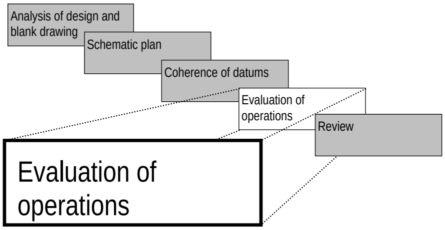
Next, there is a change of datum between turning (Op.202) and bevel gear cutting (Op.30) from the centre holes to the diameters A' and B' on the shaft. The reason is in this case is that there are not any fixtures, rigid enough, available for using the centres. The turned pinion is therefore clamped and centred with two collets on two diameters (A' and B'), and axially positioned by a stop plate on the pinion head. Note that the datums A' and B' not are the same as A and B on the design drawing. This is because the two latter ones are ground and those presently available are turned.

Spline hobbing (Op.40) is performed with centre holes as datum.

After turning, gear and spline cutting, follows heat treatment, grinding of shaft and lapping of gear. During this transformation to a finished part, there are two more changes of datums. The first one considers the centre holes [a'-b'] whose relationship to the entire part may be displaced by distortion during the hardening. They are therefore denominated as [a-b] in this new state. Then, the diameters that will be used for lapping the gear and final inspection [A-B] are to be ground relative the centre holes.

How serious these datum changes are, and how they will affect the final quality, depends on the accuracy of the transitions between different datums. This is not only a matter of capability in each operation, but of the overall capability founded on known, limited variations and a proper process plan.

6.4 Evaluation of operations



It is now possible to evaluate consequences of choices made in the present plan in order to find out how well the process will work. The overall target is to get a process that behaves as expected. The procedure starts by looking at the last operation in the manufacturing sequence and proceeds in reverse order to the first operation.

Each operation should be tackled as described in chapter 4.4 , but in this pinion case, there will be a focus on exemplifying two operations; turning and bevel gear cutting. Assume that the other operations are handled in the same way, following the reversed operation sequence.

Gear cutting

1. *What is the operation principally intended to achieve?*

   * Create a generated bevel gear by face milling, according to a gear data sheet denominated “Summary 123”.
   * It should be possible for the gear to be lapped together with the mating gear of the crown wheel.

2. *How is the workpiece really machined or treated in the operation?*

   * The gear will be cut, but there will also be burrs and sharp edges left.

3. *Which prerequisites must be fulfilled by earlier operation(s)?*

   * The pinion shaft must be turned within specified diametrical and surface tolerances to enable it to be clamped in a proper way.
   * Datum face on pinion head must not have more than 10 μm run-out in relation to clamping diameters A' and B'.
   * No un-machined surfaces are allowed on diameters for clamping or the pinion head.

4. *Can this operation be integrated with another operation?*

   * No

The following aspects are also considered for the gear cutting operation:

- Datums created in this operation
  - The gear will not be used as a datum later on in the process.
- Material conditions
  - The forged blank should be annealed for achieving good cutting performance.
  - It is not known if and how the gear cutting process affects the material structure. It cannot be excluded that there is an effect, but the consequences are estimated as insignificant.
- Principles for locating and clamping-points
  - A one-piece collet and a stop plate do the clamping and positioning. The collet centres and clamps the shaft on two diameters (A' and B') and simultaneously pulls the pinion head against the stop plate for axial positioning.
  - The contact area between tool and workpiece is indicated on the template for the gear cutting operation.
  - The collet has smooth surfaces for clamping the pinion shaft.
  - Needed clamping force in relation to cutting data is specified by the tool manufacturer.
  - There is a pulling effect when collet is closing around the pinion shaft. This brings the pinion head datum feature against the stop

plate for axial positioning.
It is judged that there is no risk of excessive deflection of the pinion head due to cutting forces.

- Cutting data
  - Feeds and speeds are determined for achieving the right quality of the gear, including surface, and a proper cutting tool life. This is difficult to predict and own experiences or recommendations from machine and tool suppliers will give values to start with.
- Cutting tools
  - The cutting tool for bevel gear production is in many aspects defined by the gear design. This implies that it is only in some aspects that the process planner can choose the characteristics of the tool.
- Environmental aspects
  - Oil is used during gear cutting.
  - The workpiece is wet after finished operation and needs to be washed before testing and case hardening.
- Temperature
  - The pinion will be heated due to cutting process and warm cutting oil.
- Measuring
  - Conventional gear measuring machine.
  - Clamping of the pinion between centres combined with a floating driver for the rotation.
  - Datum surfaces A' and B' are initially measured by the probe and then evaluated as datum feature A'-B'.
  - Measure the first three parts of a batch. Continue with intervals depending on the capability of the gear cutting process.
- Capability - expected quality
  - To evaluate this, tolerancing of the entire process plan must be performed and performance of all operations until gear cutting

must be known. (This is addressed as a matter for further research in chapter 5.)

- Part loading, unloading and transportation
  - There is a risk for deformation and damage of the surfaces used as datum features for gear cutting due to the handling of the workpiece with a robot. The same datum features are also used when testing the gear.
  - When putting the pinion shaft into the collet chuck, attention must be paid to avoid interferences to the thread, spline or datum features on the shaft.
  - To guarantee axial positioning against the stop plate is air-sensing technique needed.

Turning

1. *What is the operation principally intended to achieve?*

   * Cut the blank free from forged surfaces and into a shape that will correspond with dimensions of the finished part, apart from the geometries of gear, spline and dimensions that will be ground.
   * Create good datum surfaces for gear cutting

2. *How is the workpiece really machined or treated in the operation?*

   * This is performed in three steps:

     1. Preparation of clamping diameter for the "floating jaws", with face driver engaged.
     2. Rough machining with both face driver and jaws to reach required torque for rotating the workpiece.
     3. Finishing with only face driver.

     Datum for turning is the common axis between centres.
   * When applying the face driver to the end surface of the pinion shaft the material will be deformed by the penetration.

3. *Which prerequisites must be fulfilled by earlier operation(s)?*

   * The forged blank must be prepared with machined end surfaces and get the right length.
   * Concentric centre holes with smooth and clean surfaces without any burrs.
   * Maximum 1 mm run-out to guarantee clean cut

4. *Can this operation be integrated with another operation?*

   * Yes - there is a possibility to have a machine tool that also performs the end-machining, centre drilling and spline hobbing.

The following aspects are also considered for the turning operation:

- Datums created in this operation
  - A', B' and face on left side of the pinion head are finally turned by a finishing tool and adapted cutting data.
  - Run-out on datums less than 10 μm is expected.
  - $R_{max} \approx 2.3$ μm ; (f=0.15 mm/rev ; r_ε=1.2 mm) [6]
  - These datum features must be handled with care
- Material conditions
  - The forged blank should be annealed for achieving good cutting performance.
  - A relatively soft material, prone to be damaged.
- Principles for locating- and clamping-points (see Figure 6-26 and Figure 6-27 on page 100)
  - The workpiece is first positioned and clamped axially between centres. Then, two devices are then used as supplements:
    1. Face driver – used during the complete turning cycle.
    2. Retractable jaws – only used during roughing.

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[6] $R_{max} = f^2 \cdot 1000 / 8 \cdot r_\varepsilon$
f = federate
r_ε = tool nose radius
(Sandvik Coromant, 1995)

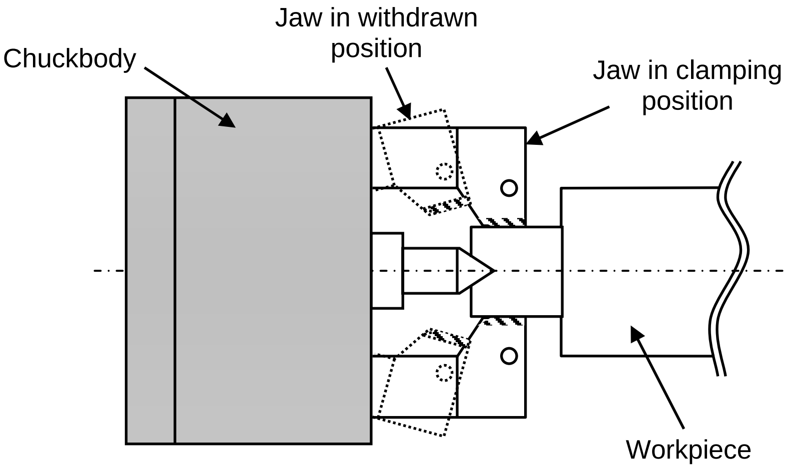


Figure 6-26 Working principle of shaft chuck for turning with retractable jaws.

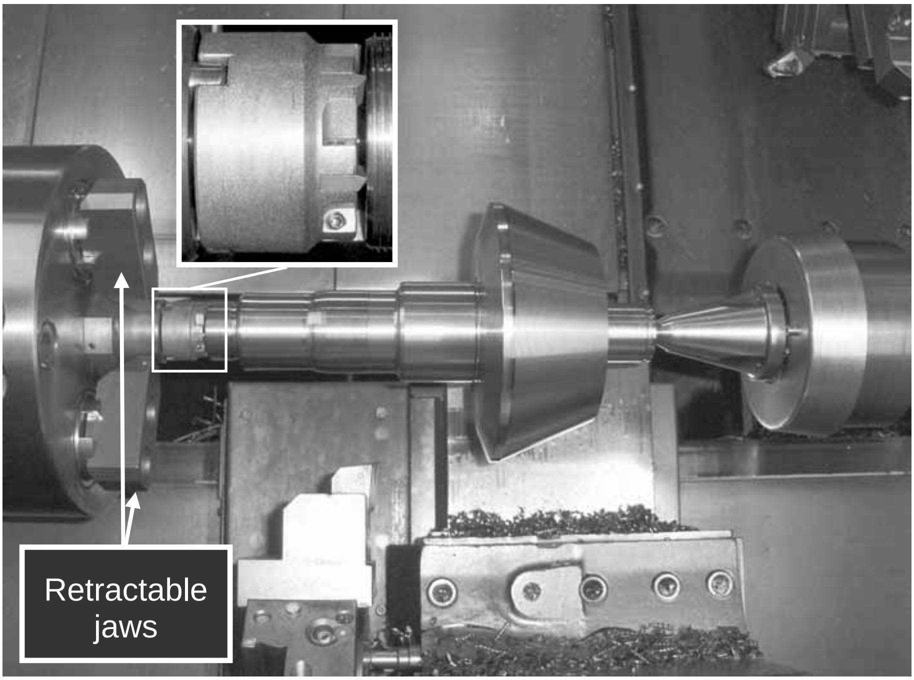


Figure 6-27 Pinion between centres in a machine tool for turning. To the left is the face driver (enlarged view) engaged into the pinion end surface. The retractable jaws are withdrawn.

The face driver is engaged in the pinion shaft end in two steps after the centres are applied. First with an axial force, that gives appropriate penetration. The force is then decreased to guarantee a good contact between chuck centre and centre hole.

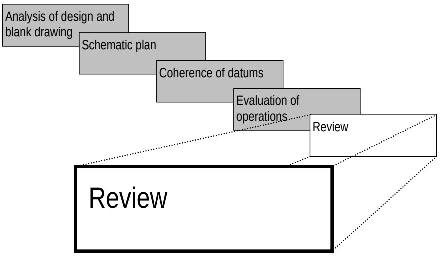
The “Floating jaws” are needed to resist cutting forces during roughing. The three jaws are applied on the left diameter of the pinion shaft, and must <u>not</u> move the centre hole out of position from the chuck centre!
The jaws are serrated to get enough grip. The clamping surface will be finished after the jaws are subtracted.

- Cutting data
  - Cutting forces must be calculated to determine the expected deflection of the pinion during roughing.
  - Cutting data for turning of datum surfaces will be adapted to achieve good surfaces, cylindricity and run-out.
  - Risk of chatter when roughing must be observed during a test run.
- Cutting tools
  - Conventional tools for external turning
  - Extra attention must be paid to how cutting depth can vary during roughing
  - Good chip forming is essential, especially when finishing
- Environmental aspects
  - Wet or dry machining is possible
  - Fixture, centres and centre holes must be kept clean to avoid quality problems when positioning and clamping to workpiece.
- Temperature
  - Temperature of blank is assumed to be within +/- 5°C from the workshop temperature.
  - Marginal increasing temperature from turning in wet conditions.
- Measuring
  - Measure when the pinion is vertically placed between centres

- Measuring of diameters with external micrometers or comparative measuring with snap gauges
- Measuring of height (length) with a height meter
- To decide the required accuracy of the measuring equipment that will be needed, the tolerances must finally be defined and compared to the capability of the measuring tool
- Measuring of angles (ex. pinion head) in a CMM

* Capability
  - as with the gear cutting, tolerances must be defined to suit the entire process plan for the pinion.
* Part loading, unloading and transportation
  - Loading and unloading with gantry loader from the top of the machine tool
  - When loading, the centre holes must coaxial within +/- 1 mm to the centres in the machine tool
  - When unloading, gripping is not allowed on the datum surfaces A' and B'
  - Transportation to the next operation on a pallet conveyor system. Pallets must not support on the datum surfaces

6.5 Review



During the work with the schematic plan, a manufacturing sequence was defined in reverse order, starting with the requirements on the finished part.

Apart from grinding of pinion shaft and lapping of the gear, the geometry is created in soft conditions (before case hardening). The soft machining operations are end-machining/centre hole drilling, turning, splines hobbing and bevel gear cutting.

It is now easier to confirm or reject the thoughts about the part design, blank design, measuring abilities, machining processes etc.

Example 1

The reasoning regarding the possibilities for measuring the pinion head, as discussed in chapter 6.1.7, can now be judged in a more objective way when the turning operation is defined. By using the same cutting tool for the turning of the tapered surfaces, the outer diameter and the left face of the head, in combination with the assurance of the CNC-program, this operation can be managed. The CNC-program is checked with regard to this by measuring angles and intersections in a CMM. However, there are possibilities for changing the definition of the pinion head design in a way that provides easier machining and control. This is in practice the same as better conditions for good capability.

Example 2

When evaluating the bevel gear cutting process in the previous chapter, it was stated that the workpiece would be warmed up during cutting. This can be compensated for in the gear cutting process but may also affect the spline hobbing operation that will follow. Depending on variations in lead-time between gear cutting and spline hobbing, the temperature of the workpiece will vary when starting hobbing. This leads to variation of spline dimensions like the measure between balls/pins.

To avoid this, the spline hobbing operation is preferably moved forward in the machining sequence and placed before the bevel gear cutting.

The template is updated due to new circumstances:

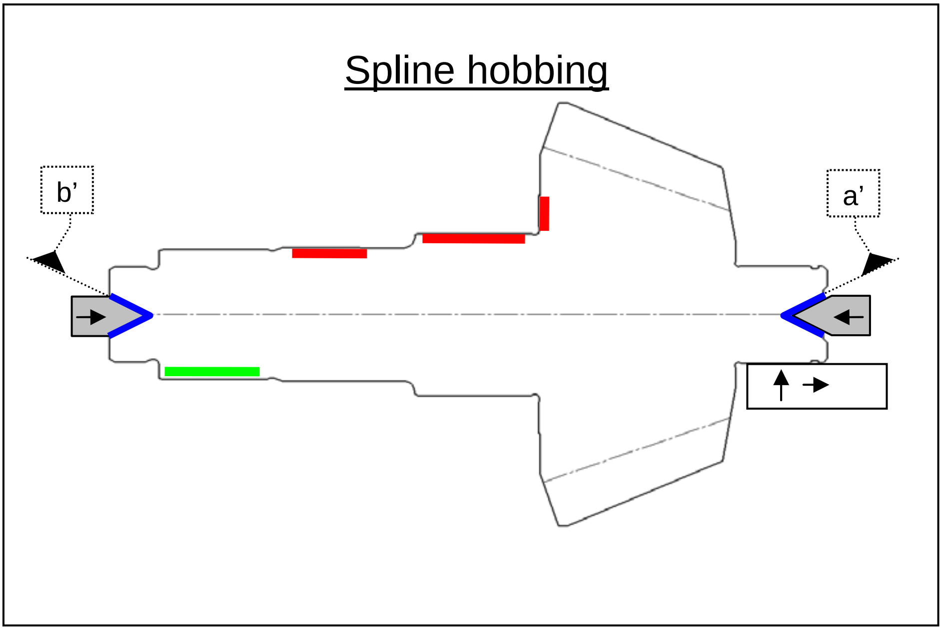


Figure 6-28 Template showing spline hobbing operation after review.

Example 3

As described in chapter 6.2.1 , section "Case hardening and tempering", the heat treatment causes distortions in the workpiece that affects the centre holes relative to the entire part. This led to the decision that the centre hole datums after hardening (a and b) should be distinguished from datums before hardening by defining the latter as a' and b'.

After taking part of an experienced heat treatment technician's point of view, it is obvious that the distortions will result in more or less crooked pinions. This affects both the pinion shaft with splines and pinion head including the bevel gear in a negative direction. Due to the tolerances of the gear and splines together with machining allowances for grinding, the pinion must be straightened after hardening.

This straightening operation is introduced in the schematic plan as a new template (see Figure 6-29). The operation is put into context and evaluated in the same way as described earlier.

Introduction of the new operation: Straightening

The way to do this is in an automatic straightening operation, where the machine first measures the deflection (run-out), then to straighten out the pinion and finally check the result. The straightening is performed by pressing the shaft as showed in Figure 6-29.

When straightening, the pinion is supported by two rigid stands. The centre holes (datums a and b) are used only for measuring and the centres are applied in that particular situation.

Measuring is carried out in two positions as indicated in the template; at spline and shaft (near pinion head).

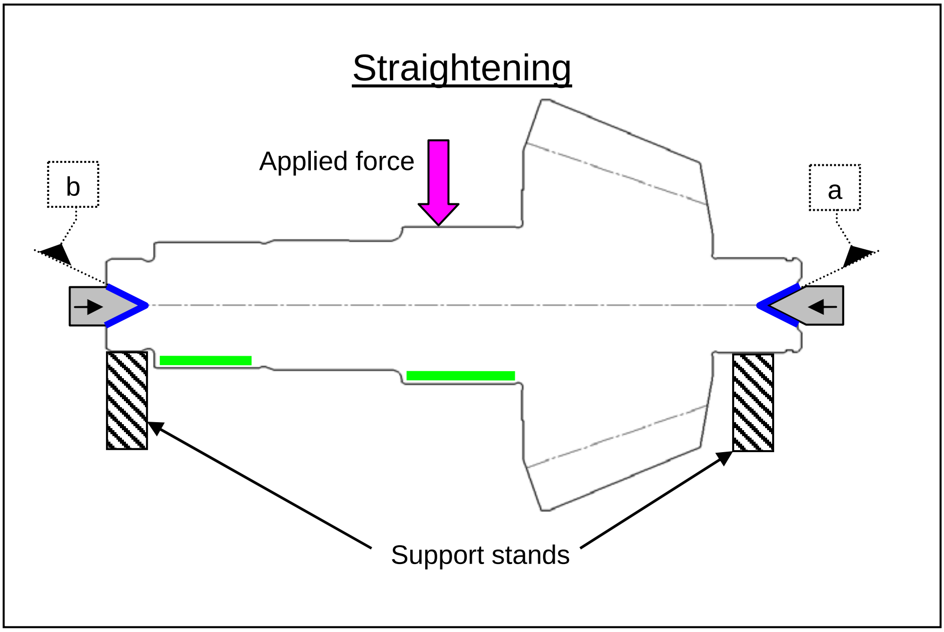


Figure 6-29 Straightening after heat treatment

The schematic process plan shall now be revised due to new facts as shown in Figure 4-2 on page 29. A new iteration will either confirm or reject the process plan as good or not good. The latter case must lead to the necessary changes of the plan until an acceptable level is reached.

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