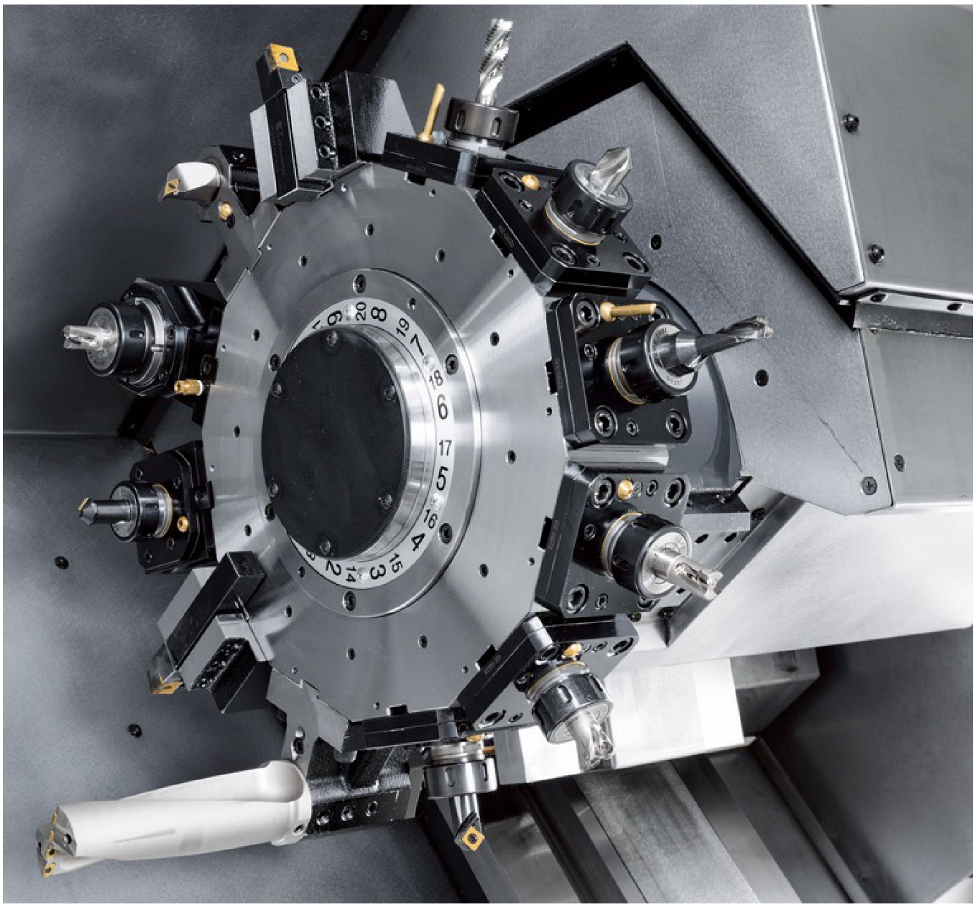
Yoshimi Ito

Innovative Process Planning Available for Machining Environment in Year 2020 and beyond



November 2022
Machine Tool Engineering Foundation

MTEF Research Guide Series No. 03

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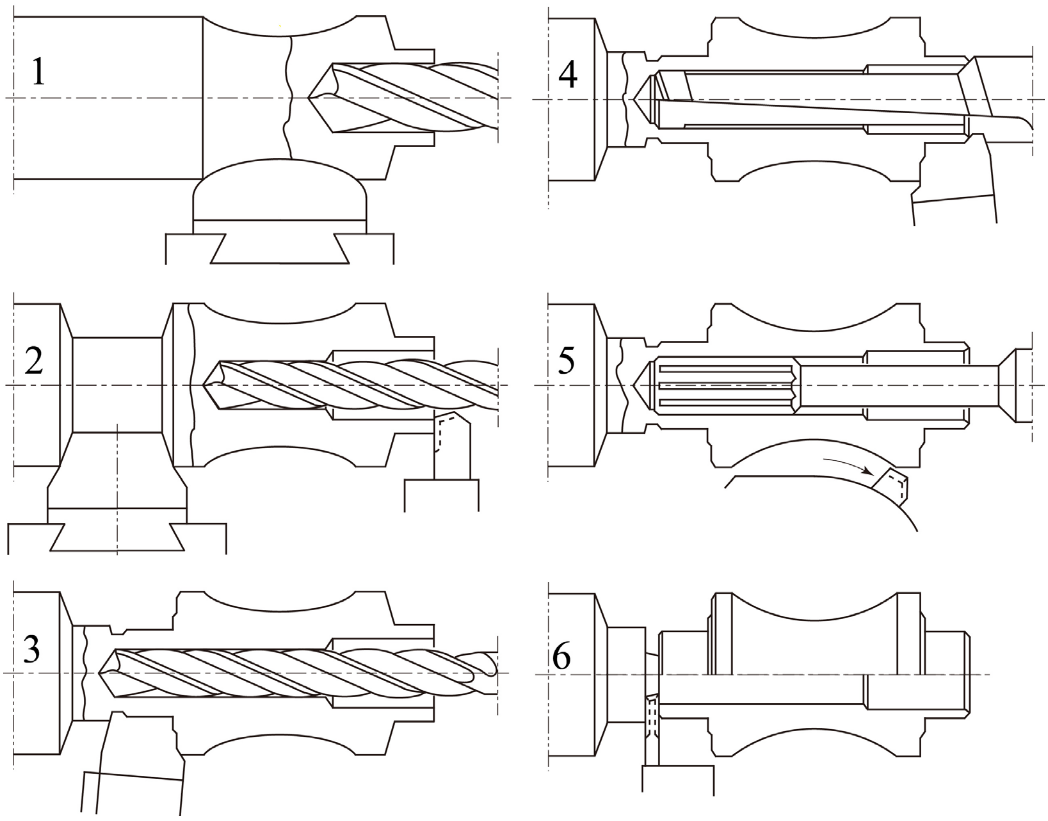

Electronic compiled by
Machine Tool Engineering Foundation in November, 2022

ISBN 978-4-909859-02-0

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Preface

In discussing the utilization technology for machine tools, primary concern is the “Machining Space”, i.e., machine-attachment-tool-work system, and as well known, the utilization technology relies on the skill and qualification of the user to a large extent even in the era of NC (Numerical Control, Numerically Controlled) technology. As represented by the “Chatter Vibration”, we cannot run the machine tool efficiently and effectively without having the mature process planner (process plan engineer) and technician, even when we can purchase it with the best performance.

To be the preferable utilization technology in satisfactory quality, a root cause of difficulties lies furthermore in the establishment of the machining space with better leverage, i.e., better combination of all the system components, which are also individually in the best functional and performance specifications. Of note, such a desirable machining space may achieve especially from the viewpoint of hardware in the case of “Chatter Vibration”.

Within process planning context, the facing problems are much more complex than those in “Chatter Vibration”, because we must discuss how to establish a desirable machining space from both the hardware and the software aspects together with considering the leverage between them. More specifically, process planning is a synergy of hardware, e.g., theory and practice in metal cutting, and software, i.e., information processing starting from the part drawing and terminating the generation of the process plan.

As a result, it has been common sense that process planning is very experienced-oriented technology, and that the only mature process planner can produce the acceptable process plan with higher quality.

Importantly, with the advent of FMS (Flexible Manufacturing System) and CIM (Computer-Integrated Manufacturing), CAPP (Computer-Aided Process Planning), i.e., computerization of process planning, became one of the necessary and inevitable software to produce automatically the process plan together with playing the intermediating role between CAD (Computer-

Aided Design) and CAM (Computer-Aided Manufacturing). In consequence, there have been a myriad of academic research activities on and engineering developments of CAPP since 1980s; however, nearly all CAPPs so far publicized are far from completion. In fact, we can eye something definite indicating the fatal shortage of the academic research into CAPP, which is caused by not modeling authentically process planning in practice. In other words, nearly all CAPPs either have been or being developed by not delving into what are the essential features of process planning in practice such as follows.

(1) Along with considering a synergy of hardware and software technologies, process planning can be characterized by its human-intelligence-based nature. The process planner must deal with the mediation among various determinants, which are in conflict relationships among one another, to obtain the preferable process plan. Obviously, we need higher skill to automatize such a decision-making procedure by the computer-aided method.
(2) The utmost primary concerns in process planning are to choose first what is the preparatory work of raw material, e.g., either forging or cold drawing, and then to determine its shape and dimensions in consideration of the material efficiency. Importantly, the engineering designer pays special attention to the form-generating procedure of the part being drawn by assuming what is a preferable raw material together with conducting rough pre-process planning.

Furthermore, we face often certain difficulties in applying the commercial software for CAPP to practice even now, because such a software involves the conversion problem of the geometrical into corresponding machining features.

Against to this context, we must, in general, recognize that CAPP at present appears as to be in mature states, although involving certain shortages as mentioned above; however, it emphasizes now that the machine tool, attachment and tool have launched out to a new horizon in the year 2010 and beyond. Thus, CAPP at present appears as to be obsolete, i.e., “CAPP at present becoming immature from mature states”.

More specifically, at issues in machine tool and attachment are now the highly machining function-integrated kind like “Mill-turn” and “Combination Chuck”, respectively. This means, there are no necessities to choose the kind of the machine tool in process planning, although it is one of conventional functions within CAPP at present. In addition, we can see a handful of innovative and novel cutting and grinding tools, which may accelerate the amazing phase changes in process planning.

As can be readily seen from the above, we face a turning point now, and must duly conduct the two-pronged activities to enhance CAPP at present: one is to improve its applicability to the practice, and the other is to contrive a new concept and due methodologies for CAPP, which is available for a future factory system, i.e., flexible-, intelligent- and smart-factory system.

Obviously, the utmost crucial issue in both the ways is to establish a “One-to-One” conversion method between the geometrical information described on the part drawing and the manufacturing-related information. In fact, there are various turning methods to generate the cylindrical part ranging from turning with a single-point cutting tool, through rotating cutter method, to turn-milling. In retrospect, nearly all CAPP at present involve such a serious problem related to “One-to-One” conversion apart from those employed “IF-THEN” rule in the expert type; however, we must remember that “IF-THEN” rule is far from fruition. Intuitively, to solve the “One-to-One” conversion problem, one of powerful remedies appears to incorporate the decision-making procedure of the mature process planner after visualizing it by certain methods.

In consideration of both the essential features in CAPP and the new horizon upheaving CAPP at present, this book describes first the basic knowledge about CAPP, and reviews its present perspectives. In due course, the book discusses then the innovative driving factors in the machining space, which will induce the marked phase changes in CAPP at present and in very near future. Finally, the book proposes a new concept for CAPP available for the

future machining space, which is based on the thinking ways and thought-patterns of the mature process planner.
Summarizing, the book discusses what are R & D (Research and Engineering Development) subjects for CAPP, which is expectable in very near future together with considering the rapidly changing states within the machining space. Thus, the book is very suitable for young researchers and engineers who are interested in and attracted to CAPP of advanced type. Importantly, ***the author will suggest obviously the due "R & D" subjects by using the "Bold-Italic"*** within the main body, whenever necessary. Furthermore, to avoid unnecessary confusion and complexity, the book discusses mainly CAPP for "Axis-symmetrical rotational parts", which can be finished by TC (Turning Centre). In this context, we must mind that TC is one of advanced types of NC turning machine, and "Mill-turn" is a synergy of TC and MC (Machining Centre).

November 2022

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Professor Emeritus Dr.

Abbreviations

ACC: Automatic Chuck Changer
AJC: Automatic Jaw Changer
CAD: Computer-Aided Design
CAM: Computer-Aided Manufacturing
CAOP: Computer-Aided Operational Planning
CAPP: Computer-Aided Process Planning
CIM: Computer-Integrated Manufacturing
GT: Group Technology
FCIPS: Flexible Computer-Integrated Production Structure
FMC: Flexible Manufacturing Cell
FMS: Flexible Manufacturing System
MC: Machining Center
NC: Numerical Control, or Numerically Controlled
QFD: Quality Function Deployment
TC: Turning Center

Contents

Chapter 1 Introduction

There have been no changes in the essential roles and characteristic features of process planning including its computerization, i.e., CAPP (Computer-Aided Process Planning) since 1960s. In short, the production system consists of the "Material (hardware) and Information (software) Flows", and also we can represent the product lifespan by the "Production Morphology" as shown in Fig. 1.1. The production morphology is a wider scope of hardware-oriented product lifespan, and thus it is better to discuss process planning from the viewpoint of information flow.

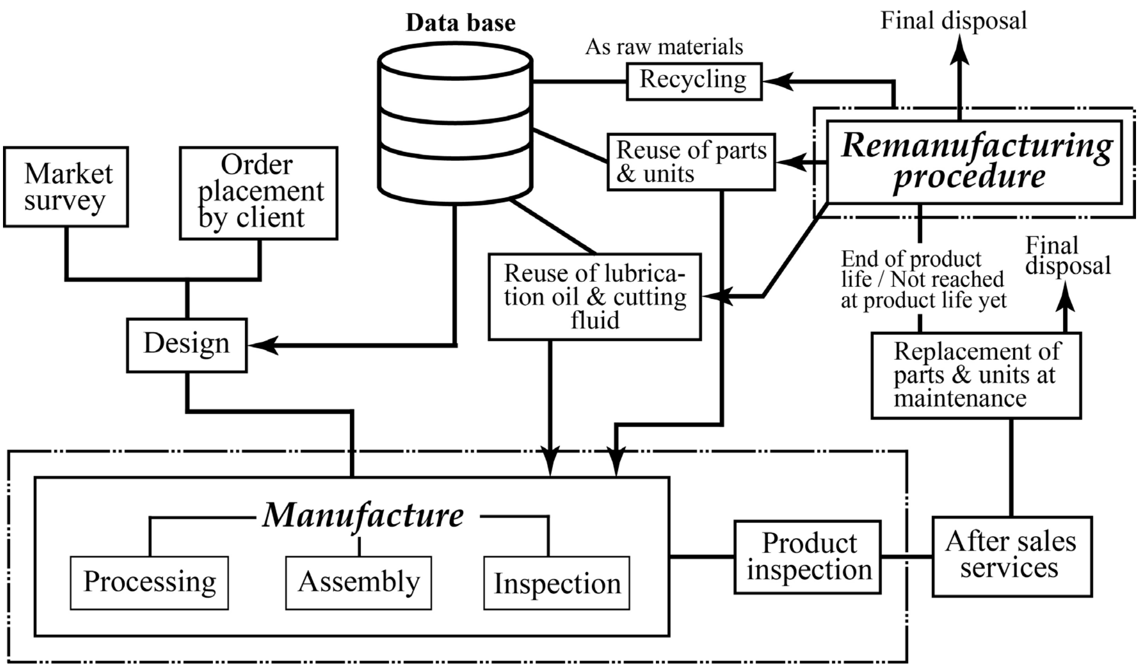

Fig. 1.1 Concept of production morphology

Within the information flow, process planning plays the role of the interface (linkage) between the "Design" and the "Manufacture" in Fig. 1.1, especially converting the geometrical information on the part drawing into the manufacturing-related information, which is a "Must" in finishing the work (part or component) and assembling all the components necessary to the product. Intuitively, the properties of manufacturing-related information differ completely from those of geometrical information, and such characteristic features provide process planning with the very experience-dependence aspects.

At present, CAPP is in leading position with the advance of CIM (Computer-Integrated Manufacturing) and FMS (Flexible Manufacturing Systems), where the former and latter are roughly software- and hardware-oriented technologies, respectively. Of notes, the utmost advanced CIM and FMS were duly in strong fusion, resulting in FCIPS (Flexible Computer-Integrated Production Structure) in 1980s (Ruth, Ito 2018), and one of its successors has become the "Smart Factory Systems" in the 2000s (Ito 2017). Even in the most advanced CAPP in the smart factory systems, without doubts, we can observe its experience-dependence features to a large extent.

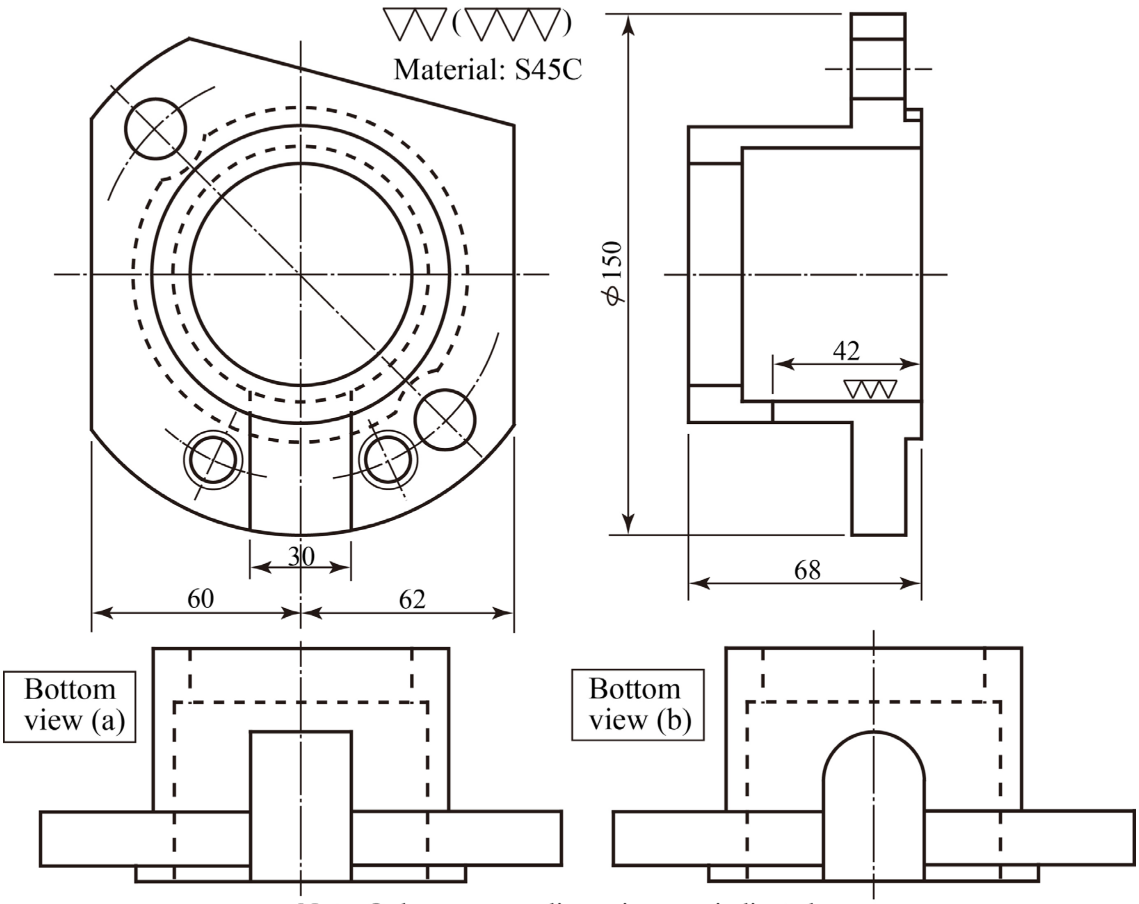

Fig. 1.2 Grass root-like knowledge necessary and inevitable in process planning

Importantly, we need knowledge about various “Form-generating Technologies” with wider and narrower scopes in process planning. For example, such technologies range from the “Form-generating Movements in Machining Space” to the “Axially Directional Orientation of Cutting Tool in Tool Layout”.

Figure 1.2 shows such a grass-root like knowledge related to the tool layout in the turret head, and it also suggests the very importance of paying the special attention to process planning when producing the part drawing.

More specifically, there are no apparent changes between both the part drawings, apart from the end shape of long groove, either “Round” or “Square” as shown in the bottom view of Fig. 1.2. In contrast, both the machining time and the cost reduce considerable in the case of “Square Groove”, because we can set the square end mill as same axial direction as those of boring bar, drill and tap at the tool seat of the turret head.

This means, we can use the same axial feed in the end mill as others; whereas we must use the radial in-feed and axial feed to generate the groove of round end, even when using the square end mill. In addition, the end mill is liable to deform in the latter case, resulting in the deterioration of the machining accuracy.

As can be readily seen from the above, we must be aware of it that process planning for a work differs more than expectation from the other, even when the shapes and dimensions of both the works are very similar. As typically shown here, process planning in practice should be carried out with leverage of wider scope, e.g., linkage between CAD (Computer-Aided Design) and CAM (Computer-Aided Manufacturing), and with narrower scope, e.g., grass root-like finishing method of the work.

Admitting that CAPP at present does not change its essential features as same as those from the past, and involves certain shortcomings in its applicability to the practice, nowadays CAPP faces an upheaval of new horizon in the machining space, i.e., machine-attachment-tool-work system. In fact, such a new horizon results from a holistic effect of the enhancement of individual technology within the machining space than ever before, as suggested in the following.

(1) Prevalence of the machining function-integrated kind like TC of twin-spindle type.
(2) Innovation and new contrivance in the chuck and tool of modular and combination types.
(3) Development of tool with innovative function and performance like "Parting-off Tool Available for Reverse Cylindrical Turning (Turn-top)".

A new horizon mentioned above appears to duly induce considerable changes in CAPP, and thus a quick note to suggest what is under way in CAPP in very near future is as follows.

"The more versatile a machining method by using the innovative form-generating concept, the more necessity is to establish its effective application to CAPP"

In fact, CAPP being used may become obsolete by growing the innovation of the form-generating function in the machining space, and thus we must establish a new method for CAPP to actively apply such innovative functions to it. In addition, the academic research into CAPP so far deals with the facing problem by narrower scope, but not with wider scope, i.e., that only considering the spot-like material removal technology, but not the form-generating movement of machine body. In due course, it is better to discuss CAPP as one of the total software issues within the machining space together with concerting with its hardware aspect to a lager extent. In contrast, the chatter vibration and thermal deformation can be considered as those mainly related to the hardware aspect within the machining space.

As will be clear from the above, we can say simply that CAPP is to mediate CAD and CAM, and that CAPP is in mature states; however, in consideration of both the essential feature in CAPP and the upheaval of innovative technologies in the machining space, we must now re-investigate what is a desirable CAPP hereafter. Importantly, we need again to delve into the following fatal problems involving within CAPP at present.

(1) Establishment for “One-to-One” conversion rule of the geometrical information into the manufacturing-related information. In this context, we must be aware that the work can be finished by the preferable integration of form-generating movement within the machining space, i.e., synergy of primary and secondary movement functions of the main body of the machine tool itself and secondary movement functions of the attachment and tool.

Simultaneously, we must investigate

(2) an innovative concept of CAPP in very near future like “Advanced CAPP of Flair Type”, which intends to use positively the human-intelligence-based knowledge.

References

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Ruth K, Ito Y. (Dec. 2018) *Flexible-Intelligent and Smart Factory Systems*. MTEF Research Guide Series No.01. MTEF.
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Chapter 2 Basic Knowledge about, Present Perspectives and Facing Issues of CAPP

With the advance of the flexible-, intelligent- and smart-factory system, CAPP grows its importance almost daily, and as can be readily seen from Chapter 1, we must urgently conduct two-pronged research into CAPP at present as follows.

(1) To enhance the applicability of CAPP to practice much more than ever before, ***the improvement of conversion function from geometrical to manufacturing-related information***, i.e., rationally processing output data from CAD to input data for CAM.

(2) In consideration of not enough applicability of CAPP at present, a proposal for innovative CAPP based on another concept, e.g., that using positively human-intelligence.

In such contexts, we must be duly aware that the driving force is amazing changes in form-generating function in the machining space. Equally, we must mind dire necessities to re-investigate what is the essential feature of CAPP, and to unveil what are unknown inhabiting fatal shortages of CAPP so far developed and commercialized.

Thus, we will discuss such issues in the following, especially clarifying the perspectives and involving problems of CAPP at present, and furthermore putting main stress on the possibility of ***incorporating the human-intelligence within CAPP in very near future***.

2.1 What Are Primary Concerns in Process Planning

In principle, we should carry out CAPP by inputting the explicit and implicit geometrical information described on the part drawing, i.e., one of outputs of CAD, and in due course produce finally the “Process Plan (Process Sheet)”. In other words, CAPP can be interpreted as an “Information Processing” commencing from the “Determination of Raw Material” and terminating the “Production of Process Plan”. While dealing apparently with the geometrical information to produce the process plan, we must, at least, conduct the “Process Analyses”, “Ordering Necessary Processes” and “Estimation of Machining Time and Cost”. Of course, we must convert the geometrical information to those for machining and concerns, if necessary, so that the corresponding work is finished properly.

For ease of understanding what is process planning, Fig. 2.1 illustrates a sample work and its process sheet. In the process sheet of Fig. 2.1, the arrowed line indicates roughly the order of processes, and for further convenience, we describe the “Process Symbol”. In short, the process symbol is legislated by JIS (Japanese Industrial Standards) and can be converted into the “Machining Method Description”, which is compatible with the “Functional Description of Machine Tools”. Thus, the “Process Symbol” is one of the powerful enablers when enhancing CAPP at present as will be discussed later in Chapter 3.

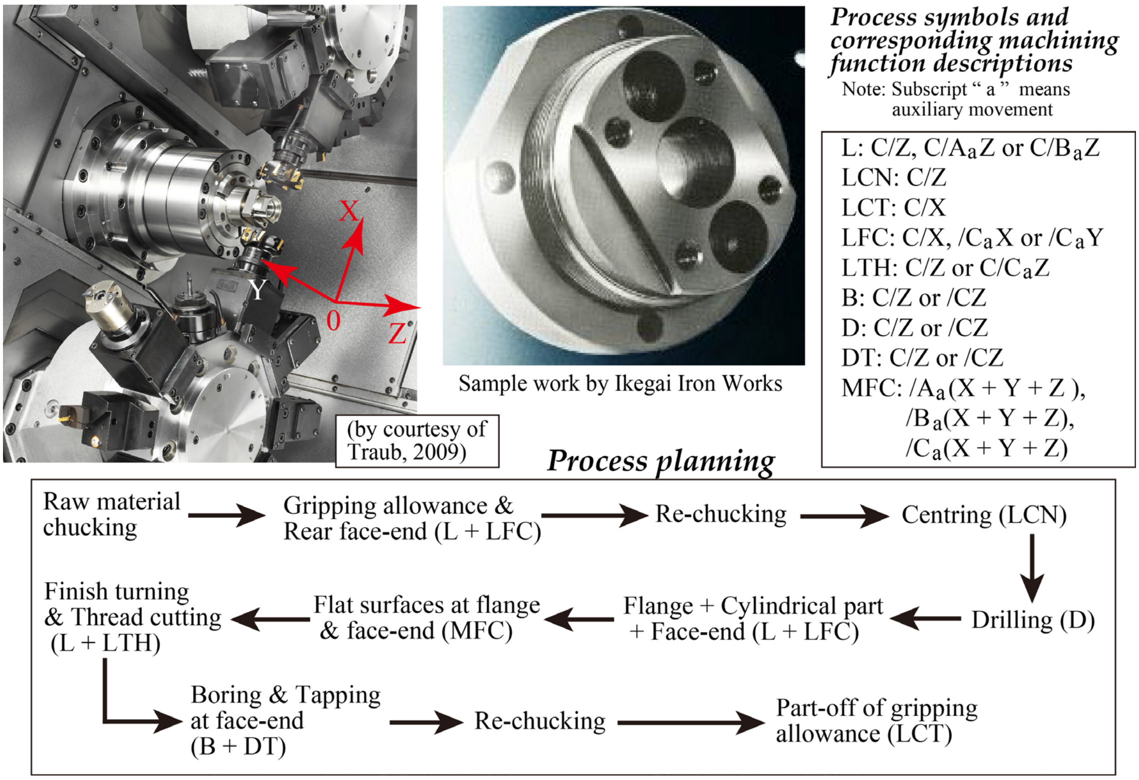


Fig. 2.1 Sample work with its process planning and conversion of “Process Symbol” into “Machining Method Description”

From the process plan shown in Fig. 2.1, process planning appears as to be very easy work for people, who is not familiar process planning; however, in determining a preferable process plan, the process planner should conduct very tedious, time consuming and pains-taking work, even when using the computerized process planning, i.e., CAPP.

In CAPP, we must firstly remind that primary concern is, no doubt, to minimize the machining time and cost, when the corresponding part is to be in reality in accordance with the indication described on the part drawing. On the strength of factory floor experience, such an economization can be facilitated by the integration of several processes, division of one process into the proper number of individual process and elimination of undue processes.

As can be readily seen, thus, it is wrong way to process the geometrical information itself, which are absolutely no relation to the machining time and cost, without converting them into machining-related information. In due course, at the burning issue is the conversion of geometrical information on the part drawing into machining-related information in consideration of differing characteristics between both the information. As a result, CAPP becomes the very experience-oriented technology, and duly the mature process planner plays the very important role by activating her/his long-standing experience and flair.

Within this context, we must be furthermore aware that the utmost difficulty is to establish the “One-to-One Relationship between Geometrical and Machining-related Information” as will be described later. In contrast, nearly all CAPPs have so far dealt with only geometrical information, e.g., information conversion of an entity (primitive volume, feature) within a part by adding and subtracting other entities, although related people assert that they dealt with the “Machining-related Entities” (for further details, see Sections 2.3 and 2.4).

Apparently, such a misunderstanding appears as to be one of causalities for the serious shortages of CAPP at present. In the most cases, thus, the research

into CAPP in academia has been carried out far afield from the practice, resulting in its achievement useless for the practical work.
Of course, we have investigated CAPP of expert system to overcome such a problem, but it is far from completion because of difficulty in establishing well-arranged "Machining-related Knowledge Database". Importantly, it appears that such a serious problem in CAPP is, in part, derived from the poor understanding of the production procedure of the part drawing.
In this context, ***a "Must" is to deeply understand what are the essential features in the production of the part drawing***, and of special note, the engineering designer always considers explicitly and implicitly the necessary processes to finish the work to certain extents.

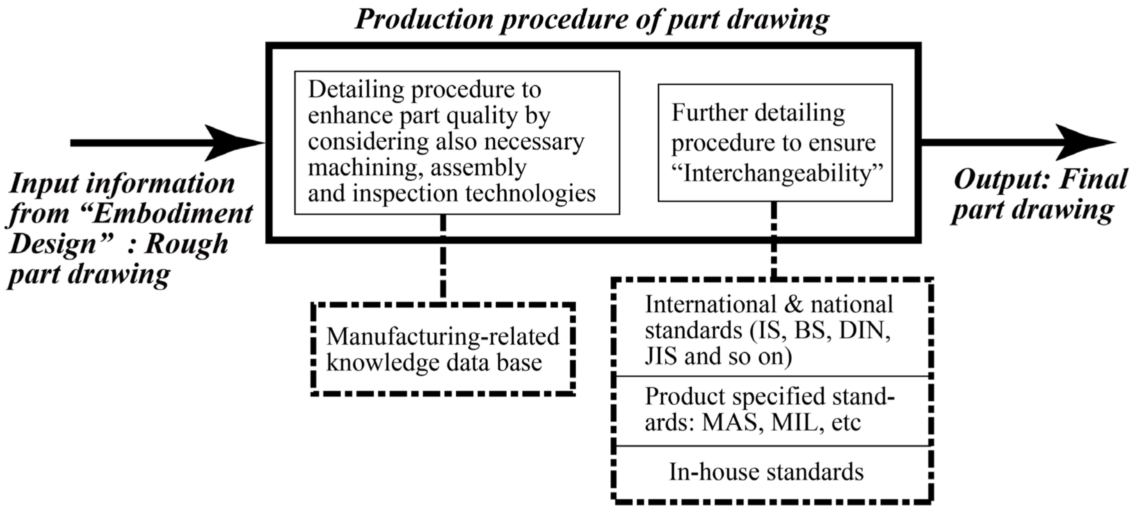


Fig. 2.2 Manufacturing-related knowledge and standards necessary in production of part drawing

Figure. 2.2 illustrates the production procedure of the part drawing, which inputs the output from the "Embodiment Design" in the production morphology (see Fig. 1.1), i.e., rough part drawing, and outputs duly the completed one. As shown in Fig. 2.2, both the machining-related knowledge and the standard play the key roles in this procedure. Importantly, it can be suggested that the detailed procedure can be facilitated with the machining-related information to a large extent, and that the engineering designer conducts such detailed procedure not only explicitly processing geometrical information, but also implicitly considering their corresponding machining methods. For example, Table 2.1 is a first-hand view of explicit and implicit information described on the part drawing, and furthermore Table 2.2 expounds on the examples for machining-related knowledge, i.e., those for work grasping, which affects indirectly process planning to a large extent.

Explicit representation	Shapes and dimensions, Machining accuracy, Surface quality, Necessity of special processing Heat treatment - Pre-machining method and allowance for succeeding process, Batch size, Work materials, and so on
Implicit representation	Processing method of raw material, Shapes and dimensions of raw material, Specification for processing method, Other parts to be integrated, Indication for part inspection, and so on

Table 2.1 Information described on part drawing

Leading item and its details		Concrete objectives
Work holding	For machining with higher accuracy	Undue alowance for grasping, use of jig, and so on “Hand-off” and “Reverse feed” machining in TC of twin-spindle type
	Datum machining for succeeding processing	———
	Grasping face quality in consideration of machining volume and accuracy	Adequate application of face driver and collet chuck
	Reinforcement of work with thin-wall	Undue “Rib” allowance
	Restriction from “Form-generating” movement	Grinding recess in gang gear
	Those related to choice of “Raw Material”	———

Table 2.2 Examples of machining-related knowledge necessary when producing part drawing

In addition to the serious problem mentioned above, another issue in CAPP lies in an ambiguity of the boundary between CAPP and CAM (exactly saying CAOP: Computer-Aided Operational Planning). Fig. 2.3 shows an information flow in CAPP and CAOP.

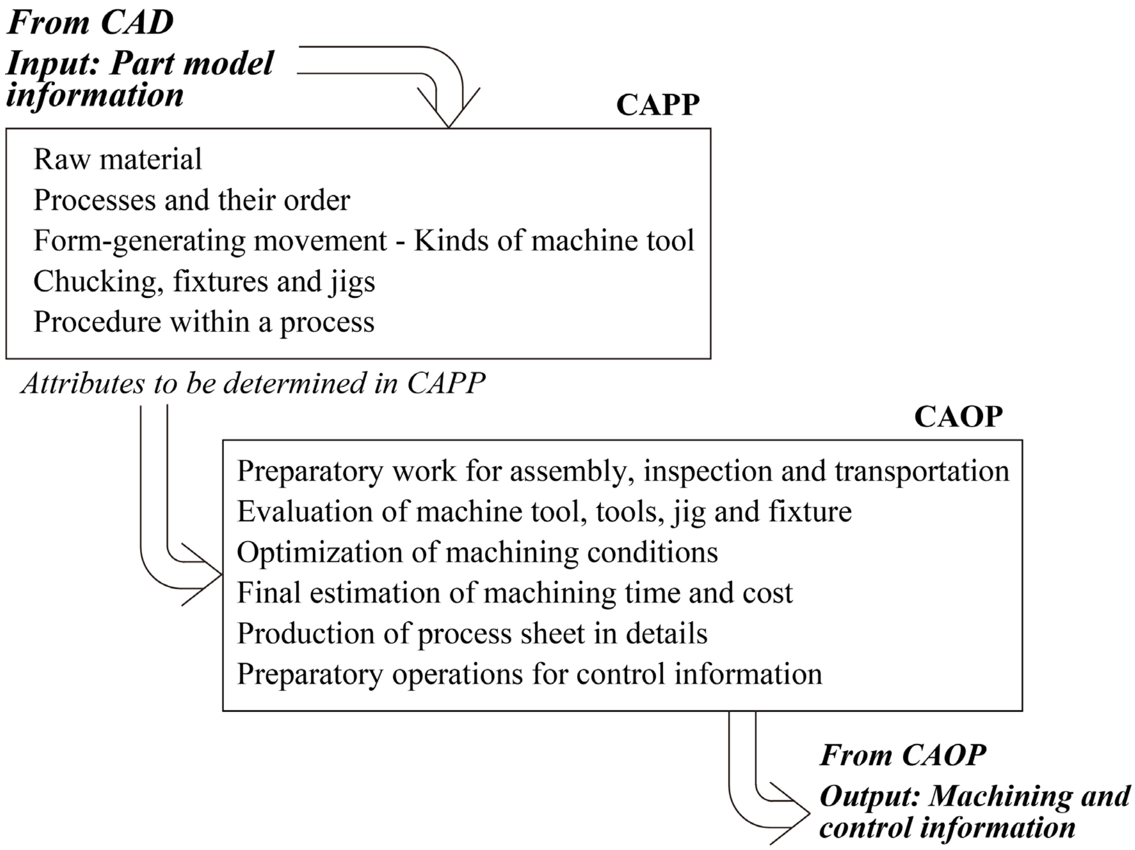


Fig. 2.3 Information flows and processing objectives in CAPP and CAOP

In this context, at issue is at which stage, either CAPP or CAOP, the standard-related knowledge should be incorporated, because as exemplified at the fitting feature of two parts, the standard as per JIS B 0405 for chamfering and rounding is closely related to process planning. In general, we can generate such a fitting feature by “Recessing” as indicated “B” in Fig. 2.4, i.e., “Orthodox way”; however, recess turning increases the machining cost, and thus we must contrive another economic way, provided that the allowable accuracy is not too much higher. More specifically, chamfering and rounding can be, as shown also in Fig. 2.4, carried out by adjusting either the side cutting edge angle or entering angle, and choosing the preferable nose radius of cutting edge in the single-point cutting tool, respectively.

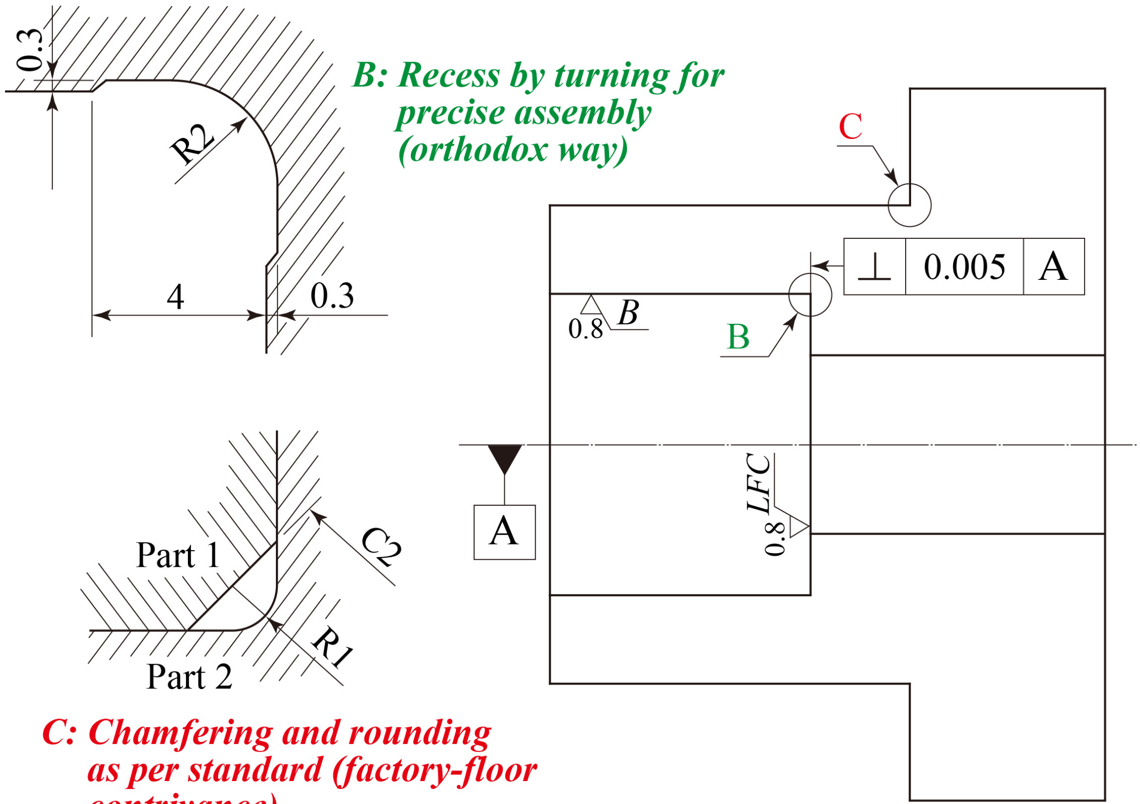


Fig. 2.4 Chamfering and rounding as per standard for facilitating higher assembly accuracy together with reduction of machining cost

In summarizing, it emphasizes that the part drawing and process planning are in mutually closer relation, and the engineering designer must always be in mind all the necessary processes to produce the part being designed to certain extent. Nevertheless, nearly all the academic investigations into CAPP have been carried out without paying any attention to such an important aspect in the part design procedure in practice.

2.2 Perspectives of and Leading Types in CAPP at Present

As already stated in Chapter 1, we have had a long history in R & D of CAPP, and thus there are an uncountable number of research papers and technical reports, and duly certain numbers of the commercialized software. In discussing what is under way in CAPP at present, we must first unveil with wider scope the past and present perspectives of CAPP. Then, we will discuss what are facing problems when enhancing CAPP at present.

Determination for machining method and tool by product model - For machining function-integrated kind / Only handling "Geometrical Primitives"
CAD/CAPP/CNC system based on 3-D solid model - By machining feature / Conversion of "Geometrical Features" into "Machining Features" by "If-Then Rule"
CAD/CAPP/CAM systems for mould machining (as per CATIA V5) - Variant type by using "Norm Process Template"
CAPP/CAM systems by "Machining Feature-basis (as per STEP)" for box-like work
CAD/CAPP/CAM systems in general
CAPP by "Machining Feature" for machining function-integrated kind of twin-spindle type - Geometrical handling of entity to be subtracted by dividing it to several "Machining Primitives" / No linkages between "Machining Primitive" and "Actual machining Method"
CAPP by "Machining Feature" for TC - Disintegration of complex shapes into "Simple Machining Features"
Processing "Machining Feature" by Graph Theory
CAPP of expert system type
Generation of alternative plans by using hierarchical structure in process and Graph Theory

Table 2.3 Examples of research subjects for CAPP in 2010s

Importantly, Table 2.3 summarizes some leading research subjects for CAPP in the 2010s. These are obtained from the literature survey, and we can see the same techniques and involving problems as those observed within R & D carried out since 1970s. In addition, we can suggest some leading hindrances when enhancing CAPP at present as follows.

(1) CAPPs having been and being carried out remain still in unsatisfactory applicability to the practical work.

(2) CAPPs in academic research depart considerably from process planning in practice, because of poor understanding its essential features.

(3) The utmost causality lies in the conversion of the geometrical information on the part drawing into the machining-related information.

(4) The very poor knowledge about the kind of the leading machine tool in the factory floor at present. In other words, a considerable number of

CAPPs rely on the old concept, in which the factory system is still based on the production cell, job shop style, GT (Group Technology) cell and so on. In fact, it is now common sense that FMS plays major role in machining the work, and thus we need not to choose the kind of the machine tool almost all cases at present. Importantly, the core machining function of FMS consists, in general, of the highly function-integrated machine tool like mill-turn.

Of these, the utmost important issue is to convert the geometrical information into the machining-related ones, and we can suggest two serious causalities as will be discussed in Section 2.4.

Admitting that there are not so much CAPPs applicable to the practice, we have had a myriad of research activities in the academia. Such states have been continued from the past, and for the sake of further discussion, it is better to classify CAPP, although we have not established the widely acceptable classification system yet.

Figure 2.5 shows a classification system, and of these, the feature-based (primitive volume) type is dominant at present, and the "Thought Model-based" type will be compatible with CAPP in very near future (see Chapter 4).

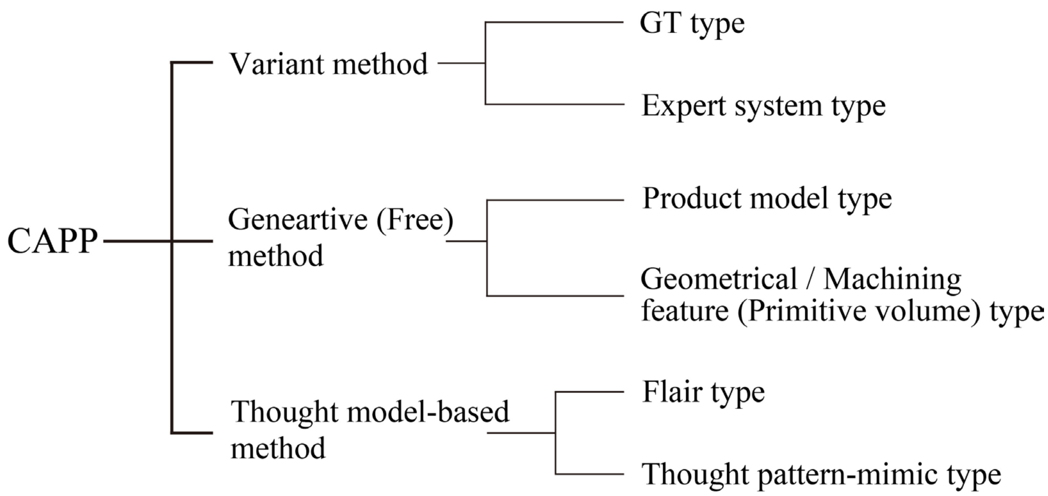


Fig. 2.5 Classification of CAPP

Of course, there are a considerable number of the hybrid types like a combination of "Feature-based Type with Expert system".

In consequence, there are another classification systems. For example, someone asserts that CAPP of generative type can be interpreted as a variant of the expert system and product model type. In addition, there are various terminologies for the “Knowledge-based CAPP”, depending upon what are the leading characteristics to be stressed. In short, in the generative method, one of the cores is the “Knowledge Structure”, which may be facilitated with the flowchart, decision trees, decision tables, pattern recognition, and so on. In contrast, in the expert system very similar to the knowledge-based type, the kernel function is the knowledge representation with “Production Rules”. In the following, a dominant type, i.e., “Feature-based” type, and two other representative types in CAPP at present will be discussed.

CAPP of feature-based type

In feature-based type, the “Feature Recognition” is one of cores, and accordingly, there are a handful of variants in the feature-based type depending upon the feature recognition. For example, the feature can be represented by the “(Directed) Graph” as shown in Fig. 2.6, where the vertex and edge correspond with the machining feature and connecting pattern among the vertexes concerned. As widely known, the graph can be converted into the “Adjacent Matrix”, which is very convenient for the mathematical treatment.

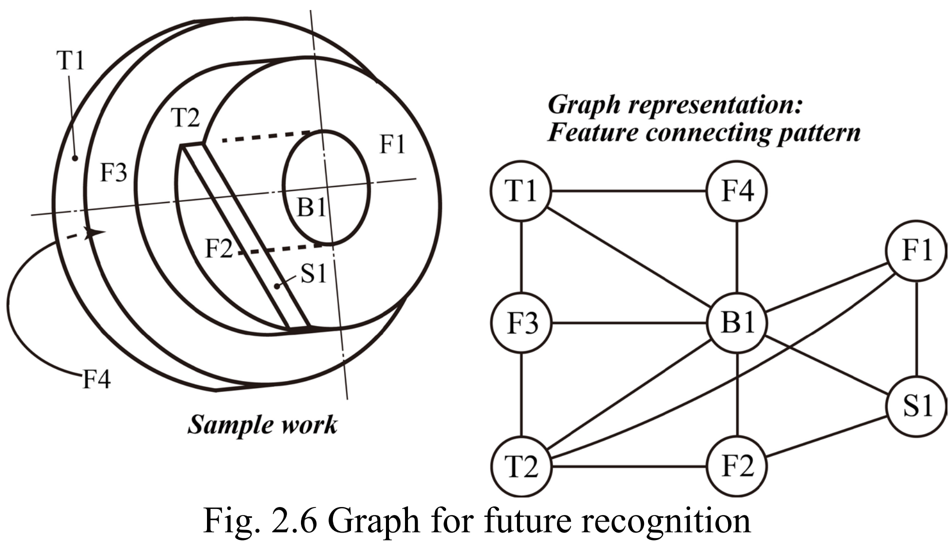


Fig. 2.6 Graph for future recognition

In addition, we can provide both the vertex and edge with necessary properties like the technical data and characteristics in connecting each machining feature, respectively. Importantly, such applications of the directed graph were already tried within the design methodology for the modular design of the machine tool (Ito 2008) and system layout of FMS (Ito 2014).
Conceptually, process planning can be interpreted to choose a set of vertexes and edges from a whole combination of all the vertexes and edges, by which all the process plans possible can be delineated. In contrast, Fig. 2.7 reproduces the sample work and its machining features delineating with the "Hierarchical Feature Tree" (Hamada et al 2012). In this case, we can produce the "Future Tree" by considering the superiority order and characteristics in generating each machining feature. In addition, the feature for reference in machining is given the utmost priority in the hierarchical structure.

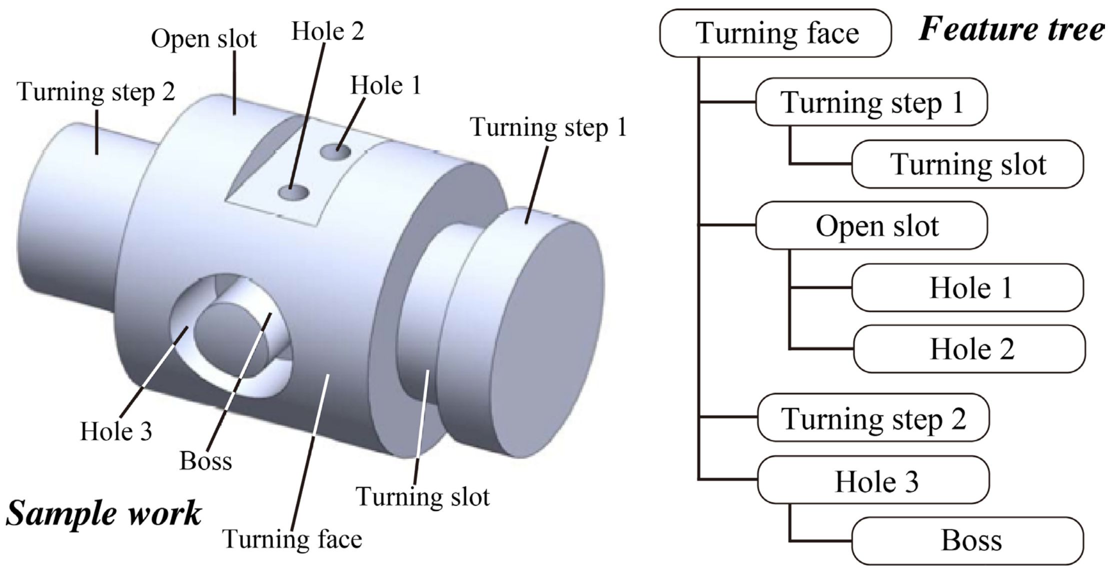


Fig. 2.7 Concept for CAPP of feature-based type
(by courtesy of Nakamoto)

As can be readily seen from Fig. 2.7, we can generate the process plan by subtracting the objective allowance from the raw material.
More specifically, process planning can be carried out as follows.

(1) Input: Shapes and dimensions of both the raw material and the finished work.
(2) After defining 16 machining features like "Face", "Step", "Boss" and "Side turning face", and also establishing the "Feature Tree of Hierarchical Structure", the choice of one candidate group together with giving the processing order.
(3) By comparing both the inputs, the determination of total removal features and their division into each feature in consideration of the priority order among them, i.e., process planning.

In short, that of Hamada et al delves into the priority order of process, interference between the tool and work, limitation of drilling depth and so on, resulting in better quality. In contrast, there remain something to be seen in relation to the systematic handling for the process integration and disintegration together with choosing the priority order in processes.

More specifically, that of Hamada involves the following problems as same as those in other CAPPs of future-based type.

(1) Without indicating anything, the shape and dimensions of the raw material is given. ***In practice, the process planner determines the raw material after concerting various attributes in confliction among one another.***
(2) Although calling the "Machining Feature", its property is still geometry-related. In addition, the authors assert that the machining feature is in good correspondence with the "Machining Method and Available Tools". There are however no guarantees between the machining feature and machining method to be finished the work.

Of special interest, ***we may enhance such a feature-based type mentioned above by coupling the hierarchical feature tree with the machining method classification of hierarchical type.***

In retrospect, the feature-based type is derived from CAD of primitive (Volumetric Element, Form Element) type, where we can generate the part by adding and subtracting the basic geometrical entities (primitives). Such CADs were developed by, for example, the CAD Centre of UK (Designing with Volumes; Cantab Press, 1974) and Technishe Universität Berlin (Spur 1977) . In addition, the feature-based type appears one of the variants of GT type, which was prevailed in the first development stage of CAPP.

CAPP of GT (Group Technology) type

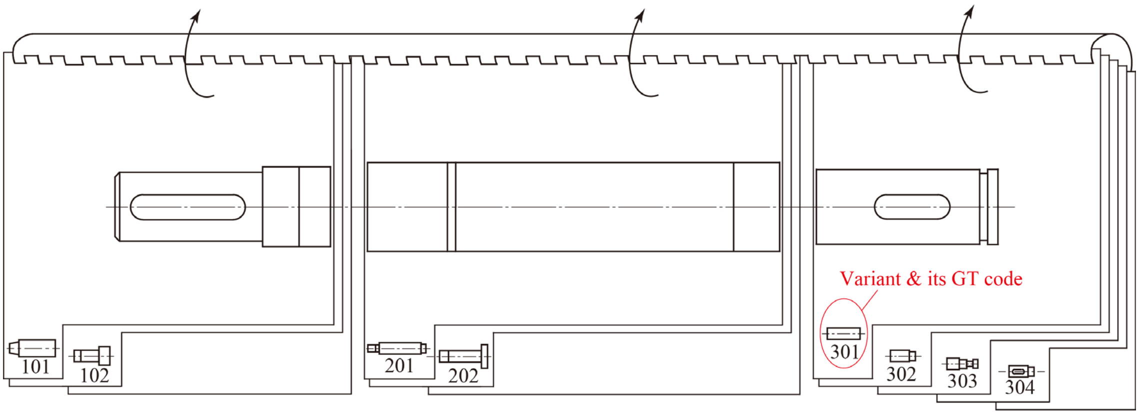
With the prevalence of feature-based type, GT type appears as to be obsolete; however, GT type is even now used in practice to some extents. In fact, GT type is very convenient when the product deployment is relatively narrow, resulting in the less variation in machining methods. Importantly, GT type is incorporated in part within the feature-based type to ease of specification of the machining method to the corresponding machining feature.

As widely known, GT was proposed by Mitrofanov of USSR immediately after the 2nd World War, and firstly aimed at the rationalization of the batch machining from the viewpoint of the cost, i.e., “Part Family Machining”. In principle, a part should be divided into several “sub-parts (Functional Complexes), and a sub-part and its variants are determined by their similarities in machining across a group of parts. In addition, the numerical number, i.e., GT code, can facilitate the identification of each sub-part.

In the part family machining, the part and sub-part with the same GT code are first gathered to consist a certain scale of group, and then machined by the corresponding kind of the machine tool, so that the machining cost is equal or lowered as compared with that obtained by the mass-production.

In due course, each GT code has its own machining method, which is verified its validity by the factory floor experiences, and thus it is very easy to apply GT code to process planning. In consequence, CAPP of GT type can be regarded as an “Experience-oriented Template Method”. More specifically, we can produce, within less processing time, the process plan by referring to the corresponding GT code for the given part drawing with the database. In fact, we can extract, without any problems, the process plan when finding the same GT code within the database, i.e., “GT Code Retrieval Method”. In contrast, we must revise duly the process plan a little bit when finding only a similar GT code, and the revised one should be stored within the database for further application (in certain cases, called “Generative GT type).

Figure 2.8 shows schematically a part consisting of three sub-parts, and by gathering process plan for each sub-part, we can produce the final process plan for a part (Szabó Z-J, Vogel F O 1975). By it, we can increase the adaptability of CAPP much wider than that for the part itself. Importantly, a kernel is thus to arrange a database, which can give us the due process plan for each GT code, reliability of which is already verified on the basis of long-standing experience.



Note: Dimensions, tolerances, surface finishes and so on necessary are duly given

Fig. 2.8 Variants in a primitive volume and their integration in GT type - Modified that of Szabó in part

In due course, CAPP of GT type has two typical hindrances as follows from the past and even now.

(1) Because of experience-based method, only applicable to the “Variant Process Planning”, but not for the “Free Process Planning”.
(2) The painstaking efforts are needed to prepare the database and the applicability is limited within a certain product.

As can be readily seen, GT is the very handy and has high potentiality, and thus later it has been also applied to CAD. We must be thus aware of it that the “Functional Section” is, at present, called as either “Machining Feature” in CAPP or “Geometrical Feature” in CAD.

CAPP of Expert System Type

As literally shown, CAPP of expert systems aims at the positive incorporation of the knowledge and flair of the experienced process planner, and thus one of the cores is the establishment of the knowledge database. In general, we can represent the knowledge by the “Production Rule”, “If-Then Rule”, and so on. ***Up to now, however, we face certain difficulties to have the reliable knowledge database, because of difficulties in the knowledge acquisition***. In addition, we must suggest that the expert system so far publicized relies considerably on the knowledge database, which don’t consider anything related to the thought pattern or thinking ways of the experienced process planner.

In other words, the weakest point in CAPP of expert system lies in the knowledge acquisition. For example, NEDO (New Energy and Industrial Technology Development Organization) run once the project research into the establishment for the “Machining Database” in 2005.

<table>
<tr><td>Netherlands</td><td>University of Twente</td><td rowspan="4">UK</td><td rowspan="4">Coventry Polytechnic
Systime Co.
UMIST
University of Aston in Birmingham
University of Edinburgh
University of Leeds</td></tr>
<tr><td>Norway</td><td>Norwegian Institute of Technology</td></tr>
<tr><td>Sweden</td><td>IVF Stockholm Branch
Royal Institute of Technology</td></tr>
<tr><td>USA</td><td>MIT, Lab. for Manufacturing & Prod.
MRA Inc.
University of Illinois</td></tr>
</table>

Table 2.4 Organizations conducted R & D into CAPP of knowledge-based type and expert system in 1980s

In retrospect, CAPP of expert system was once evaluated as to be very expectable in practice such as shown in Table 2.4. Table 2.4 summarizes a handful of organizations, at which CAPP of expert system was investigated in the 1980s; however, these were far from the practical application, because they were mainly investigated into the “Knowledge Processing” and “Database Structure”, provided that all the necessary knowledge were already obtained. In certain cases, the choice process of the kind of machine tool was furthermore included, even though TC (Turning Center) and MC (Machining Center) became the leading machining facilities on that occasion. To this end, it emphasizes that CAPP of expert system has not been improved and deployed since 1980s, and its dominant causality is derived from the fierce difficulty in the knowledge acquisition from the mature process planner. In due course, we may expect CAPP of "Thought Process-Based" type to a large extent (see Chapter 4).

2.3 Leading Issues Inhabiting within CAPP in Details

As already suggested in Section 2.2, in principle, we must foster the human resources and arrange the hierarchical database for machining method to solve a fatal shortage in CAPP, i.e., not guaranteeing "One-to-One" relationships between the geometrical and machining features.

<u>Cultivation of human resources who can understand essential facets in CAPP</u>
In general, people related to CAPP are liable to use the terminology, "Machining Feature" with uncertainty as exemplified by the following two cases.

(1) A review paper discusses what is "Manufacturing Features" in the application of STEP AP224 to CAPP for prismatic parts, and states only one sentence, i.e., "Feature extraction and translation of design features into manufacturing features" (Majstorović 2017). It sounds very easy to convert the design features (geometrical features) into the machining features; however, there are no conversions between both the features. In fact, STEP AP224 handles only the geometrical information in detail, but not indicating what is the actual machining method, i.e., apparently representing "Machining Feature", but not concretely machining method to be applied.
(2) Some researchers state that the machining feature of "Drilled Hole" can be defined from the technical data, e.g., diameter, depth of hole and drill angle, on the part drawing. This "Drilled Hole" is not the "machining

feature", but only represents the dimensions and shape of hole remaining still in the geometrical feature. In fact, we must specify, at least either twist drilling or slot drilling, which is real "Machining Feature".

Dare to say, such a wrong interpretation happens often when the software specialist manages CAPP, but she/he has not enough knowledge about machining technology and form-generating function (hardware aspects) in the machining space. In this context, we can observe a typical example in choosing the kind of the machine tool, which was very popular in the software of production scheduling in the past; however, such a function in CAPP is obsolete, and CAPP renders it needles hereafter. At present, it is common sense that ***the highly machining function-integrated kind like "Mill-turn" is primary concern in the machining space. In short, nowadays we need not any choosing procedures for the kind of the machine tool.***

Establishment of "One-to-One" relationships between the geometrical and machining features

As widely known from the past, a geometrical feature like "cylinder" can be finished by a handful of machining methods ranging from the "Cylindrical Turning (Turn Top)", through "Turning by Rotary Cutting Tool", to mill-turn (see Chapter 4). Importantly, these machining methods are in hierarchical structure, and its structural configuration depends upon what is leading "Discriminator" like "Machining Accuracy" and "Heavy Cutting Capability".

Although there have been no trials so far, the author suggests two clues to solve this crucial problem herein. One is to apply QFD (Quality Function Deployment) of hierarchical type, and ***the other clue will be interrelated the "Feature Tree" or "Feature Graph" in feature-based type with the hierarchical structure in machining method when intending to establish "One-to-One" relationship between the geometrical and machining features*** (for details, see Chapter 4).

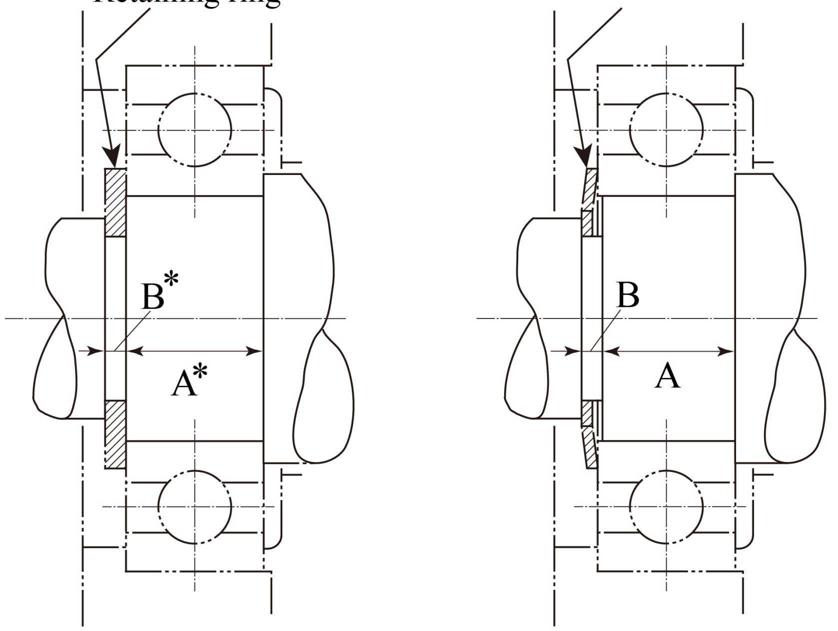
2.4 Another Crucial Issue by Nature – Essential Causality Departing Academic Research from Practical Application

In general, nearly all CAPPs deal only with the geometrical addition and subtraction of the features (primitives) without paying any attention to their machining methods. Even when discussing CAPP of expert system, it may take into consideration of the apparent manufacturing-related knowledge, but not the “Deep Knowledge”, which is not indicated on the part drawing, for example, “Leaving suitable allowance for finishing with required quality in succeeding process”.

To exploit such deep knowledge from the part drawing, we need to establish ourselves as the experienced and mature engineers. In due course, this implicit information is the utmost causality departing the achievement obtained from the academic research from the practical use. More specifically, we can suggest a handful of such “Deep Knowledge” in the engineering design as follows.

<u>Changing machining requirements by counterpart – Necessity of referring assembly drawing</u>

We face certain difficulties in understanding correctly the information described on the part drawing, and in such a case, we must refer to the assembly drawing, otherwise we cannot produce the preferable process plan. Figure 2.9 shows fixing of the bearing at the end of the shaft. As can be readily seen, fixing the bearing by “Belleville washer” is not required high accuracy in groove machining, whereas the groove should be finished with higher fitting tolerance when fixing the bearing by the retaining ring. Obviously, process plans for both the cases differ considerably from each other. Thus, we must refer to the assembly drawing to produce an acceptable process plan, or it is desirable to indicate the counterpart by using the two-dot chain line to avoid unnecessary work such as shown also in Fig. 2.9.



A, B: General tolerances
A* , B* : Tighter tolerances related to bearing and retaining ring

Fig. 2.9 Considerable differences in process planning caused by counterpart

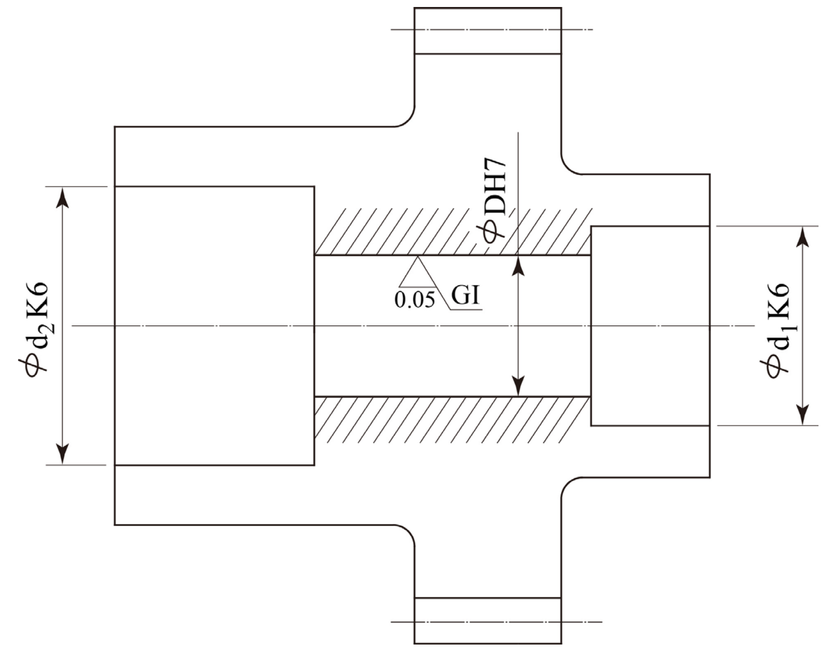


Fig. 2.10 Generation of datum for succeeding processes while cutting work

Another typical example is to provide the work with a reference for the succeeding process such as shown in Fig. 2.10. This reference is not necessary as a function of the part when assembling in the product. In contrast, it is a datum for gear grinding and also for the inspection of the gear accuracy after finishing the work, and thus there is no necessity of the heat treatment and finish grinding, although the higher fitting tolerance is required. As will be clear from the above, there is a certain change in process planning as compared with that for conventional work.

Undue allowance for grasping – Cutting-off after finishing work

There are two types: one is for finishing the work with higher accuracy, and the other is due to the restriction of the machining space, which is caused by the functional and performance specifications of the machine tool itself.

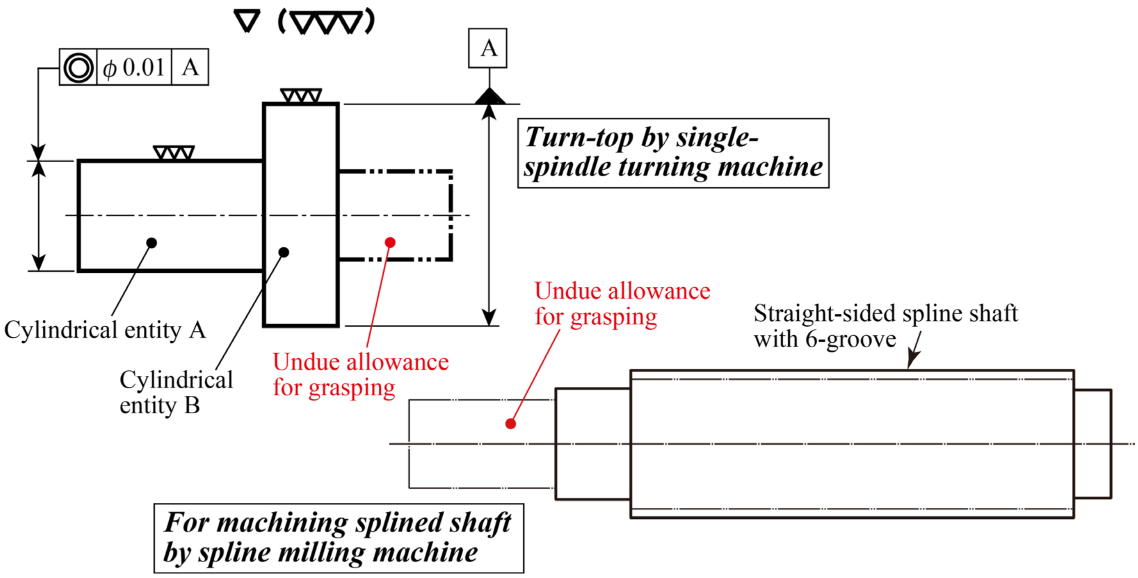


Fig. 2.11 Undue allowance for work grasping

Figure 2.11 shows such typical examples. As can be readily seen, the undue allowance plays only to hold the work by the attachment, but is not necessary as a part of the finished work. More specifically, the former is for higher accuracy turning by single-spindle turning machine. In this case, two sub-cylindrical entities should be in better concentricity, and thus we cannot use any re-chucking. In contrast, the latter is for machining the splined shaft by using a spline milling machine of specified manufacturer-make, and of course the manufacturer gives the detail of undue allowance to us.

Undue allowance for reinforcement of thin-walled work

The undue allowance is often employed to reinforce the work with thin-walled portion instead of the jig and fixture. Fig. 2.12 shows such a typical example in the case of box-like work. As can be readily seen from the work configuration, the center portion of the work is liable to deform, and thus we need to place the due "Rib" allowance. Obviously, this allowance is parted-off after finishing the work.

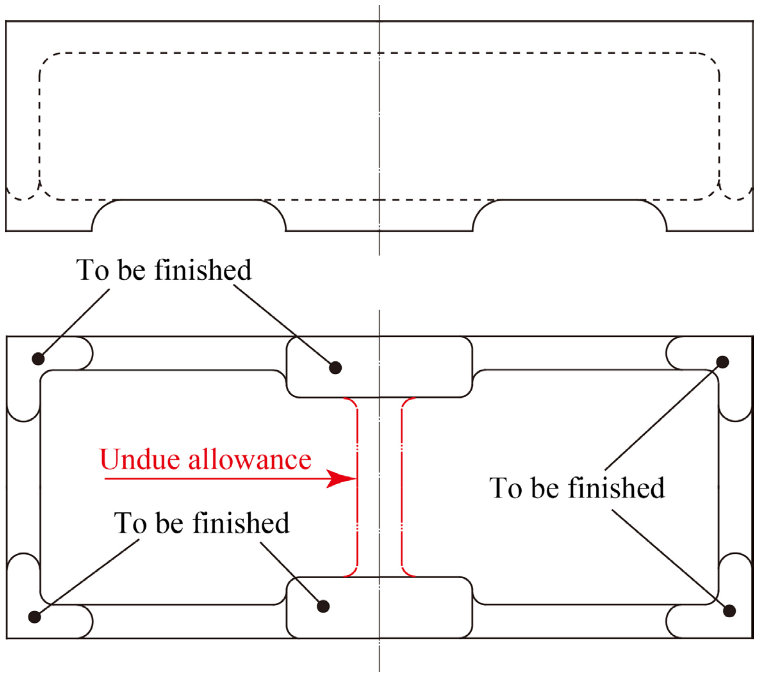


Fig. 2.12 Undue "Rib" allowance for reinforcemnt of "Thin-walled" portion of work

Restriction of machining space in gear grinding by machine of specified manufacturer-make

In not only gear grinding, but also other special processing, we have certain restriction in the shape and dimension of the work, resulting in considerable changes in process planning. Fig. 2.13 shows such a typical example in teeth grinding of the gang gear. More specifically, the grinding wheel affects the span and step between the adjacent gears, and in addition, such dimensions change depending upon the manufacturer of gear grinding machine. Thus, Pratt and Whitney developed the gang gear of combination type as shown also in Fig. 2.13. This excellent contrivance is based on the dexterous use of the splined shaft together with fine thread, and of course, both the process plans differ considerably from each other.

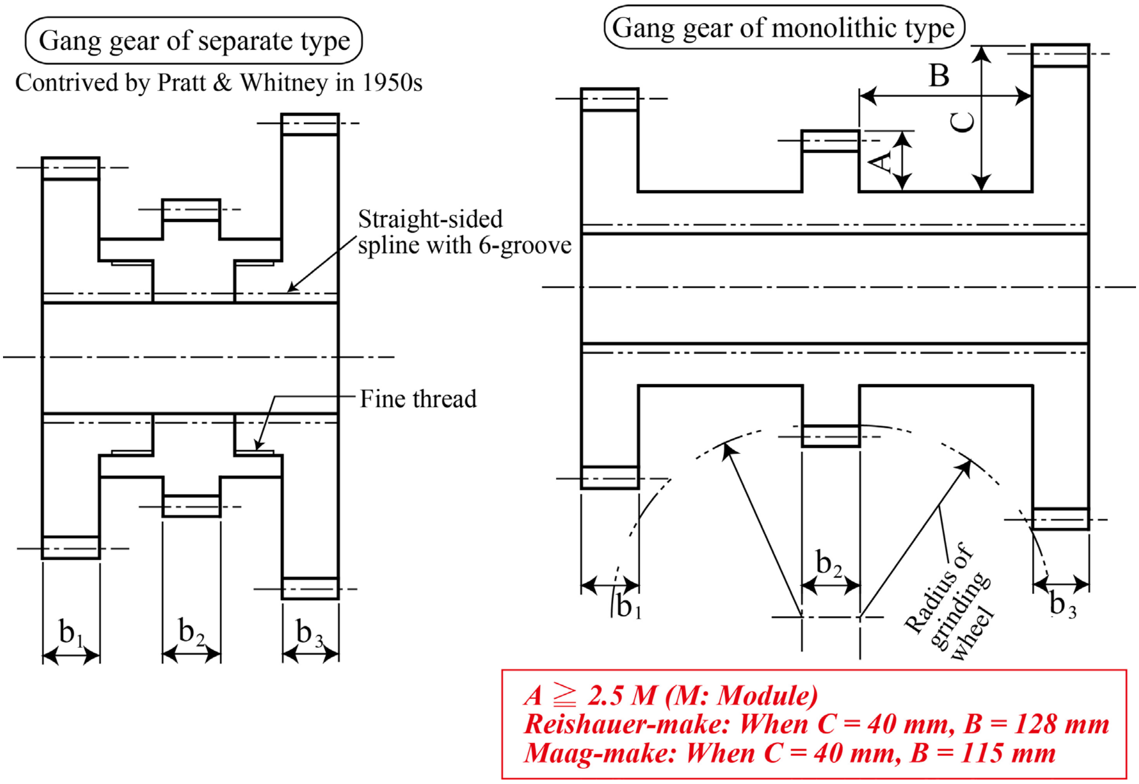


Fig. 2.13 Different restriction in allowable work dimensions for gang gear depending upon grinding machine of different-make

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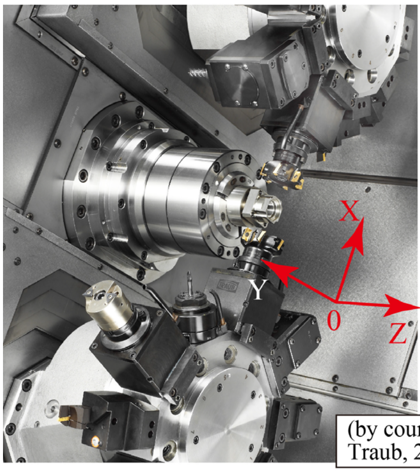
Chapter 3 Upheaval of New Phases in Form-generating Methods Inducing Considerable Changes in CAPP

In discussing CAPP, it is, in principle, very convenient to employ the "Functional Description" of the machine tool, which can represent the form-generating movement in the main body of the machine tool by using the Cartesian co-ordinate system, i.e., (X, Y, Z) and (A, B, C) (Ito 2008). More specifically, "Must" is to represent the form-generating movement in the machining space, i.e., machine-attachment-tool-work system, together with employing the "Process Symbol", which is, in general, legislated within the National Standard.



(by courtesy of Traub, 2009)

Sample work by Ikegai Iron Works

Process symbols and corresponding machining function descriptions

Note: Subscript " a " means auxiliary movement

L: C/Z, C/A_aZ or C/B_aZ
LCN: C/Z
LCT: C/X
LFC: C/X, /C_aX or /C_aY
LTH: C/Z or C/C_aZ
B: C/Z or /CZ
D: C/Z or /CZ
DT: C/Z or /CZ
MFC: /A_a(X + Y + Z), /B_a(X + Y + Z), /C_a(X + Y + Z)

Process planning

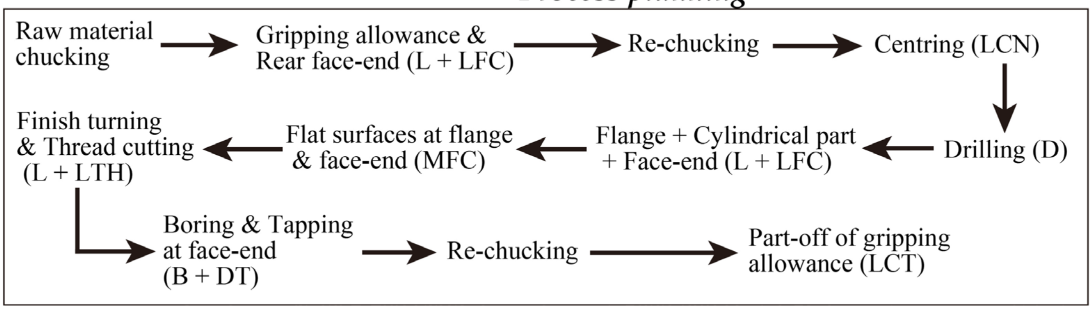


Fig. 3.1 Sample work with its process planning and conversion of "Process Symbol" into "Machining Method Description"

For ease of understanding, Fig. 3.1 reproduces a process sheet for the flange-like sample work by using the process symbol, which can be facilitated with similar description method as that in functional description (see Fig. 2.1). Thus, the process can be converted into the "Machining Method Description" without any difficulties, and then we can choose a desirable kind of the machine tool for the given work by comparing the process symbol with the functional description for the machining space.

In fact, one of the cores in CAPP is to choose the machine type within the highly machining function-integrated kind, and thus, as mentioned above, the functional description is very useful to enhance process planning hereafter; however, ***there remains something to be seen in the further applications of the functional description and process symbol to process planning.***

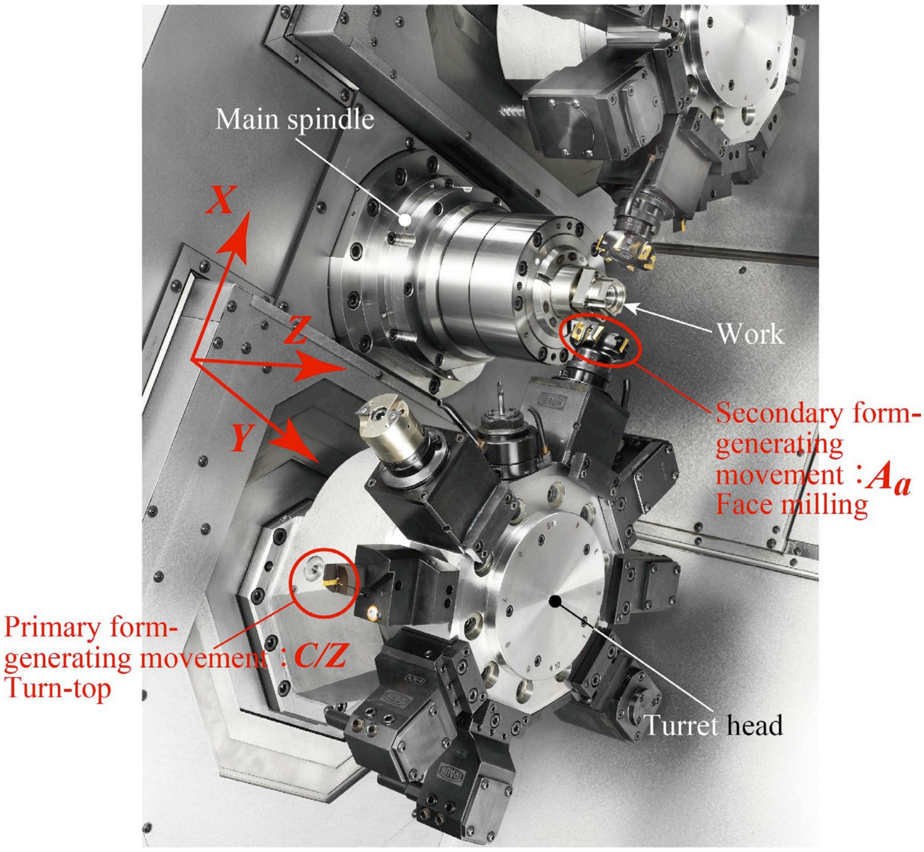


Fig. 3.2 Primary and secondary form-generating movements in main body of TC (Photograph; by courtesy of Traub, 2009)

Importantly, the form-generating movement should be classified into those of primary and secondary types, as will be discussed later, to expound their own important roles and effectiveness. In principle, the main body of the machine tool can conduct both the primary and secondary movements, whereas the attachment and tool can conduct only the secondary movement as shown in Fig. 3.2. For example, we used to apply a special boring bar and face plate in the horizontal boring and milling machine to the tapered hole boring and face turning, respectively, which can be classified into the secondary form-generating movement.

3.1 Prevalence of Highly Machining Function-integrated Kinds

TC belongs to a family of "Machining Function-integrated Kinds", and there are two representative types, i.e., those with single- and twin-spindle, as shown in Fig. 3.3. Importantly, TC can be characterized by the outstanding capability of carrying out various processing methods not only machining, but also special processing such as shown together in Fig. 3.3, where the machining method can be classified those for primary and secondary form-generating functions. For example, grinding and gear cutting belong to secondary form-generating function, although these are for machining, and obviously, special processing can play the role of secondary form-generating function.

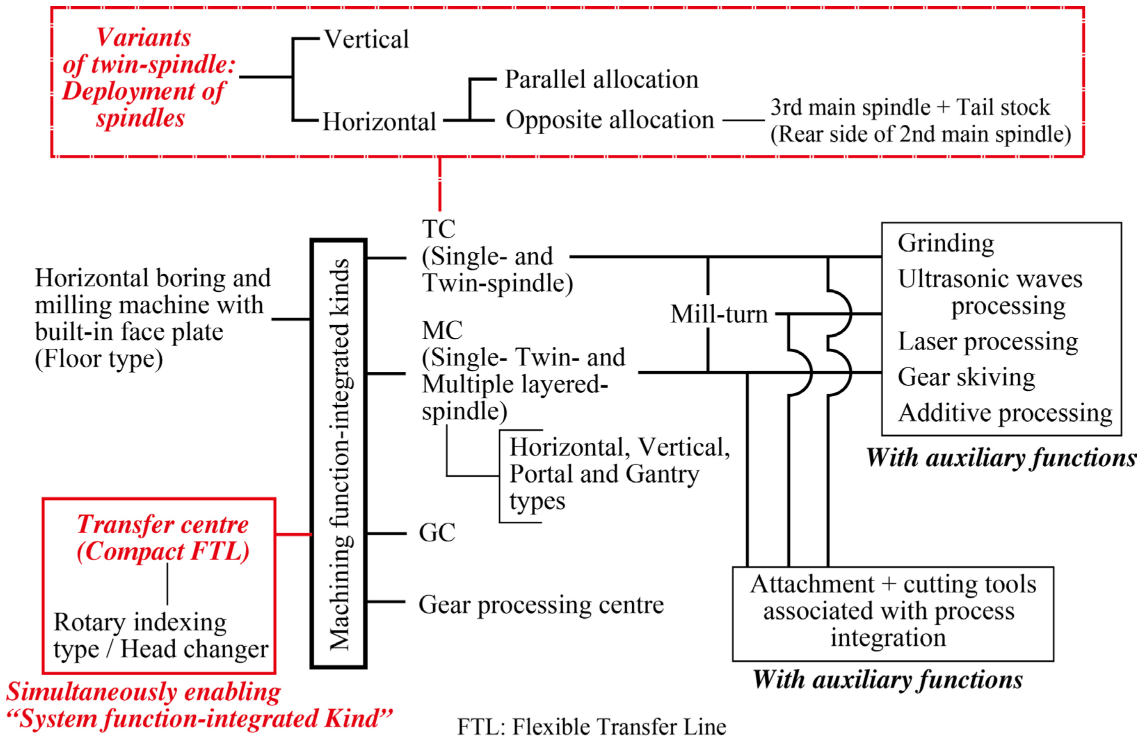
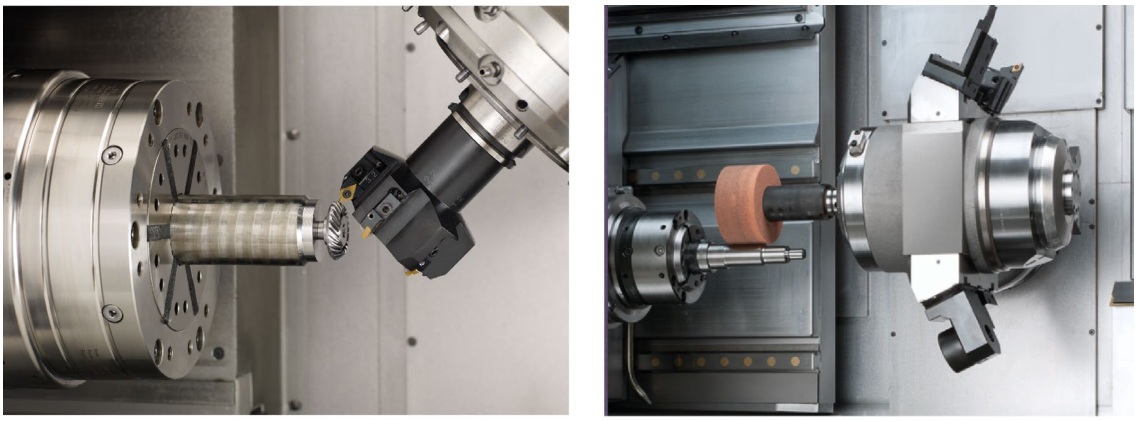


Fig. 3.3 A classification of machining function-integrated kinds in 2010s

In short, the TC can carry out a handful of leading machining methods by its primary form-generating method, and in due course reinforce its processing

capabilities to a great extent by its secondary form-generating function. Intuitively, the secondary form-generating function in TC may enhance indirectly process planning by reducing, for example, the number of other machines, which conduct individual processing, and thus we can economize in transportation and preparatory work. Of note, Fig. 3.4 shows the machining spaces in TC, where the work is being ground and gear cut.
As a result, we can guess considerable changes in CAPP with the advance and prevalence of TC as will be, for example, shown later in Fig. 3.5, although we cannot obtain the relevant and quantitative evidence for amazing enhancement of CAPP, because of company's confidentiality.



Machining space for gear cutting ***Machining space for grinding***

Fig. 3.4 Secondary form-generating function in TC

In this context, it can be furthermore suggested that TC of twin-spindle type is one of "Highly Machining Function-integrated Kinds" and may give us considerable effects on the CAPP. Thus we must first discuss what is the amazing change in CAPP, and to what extent we must consider the effect of TC of twin-spindle type on CAPP. In consequence, Fig. 3.5 compares a typical machining state of the work with better accuracy by TC of either single- or twin-spindle type.

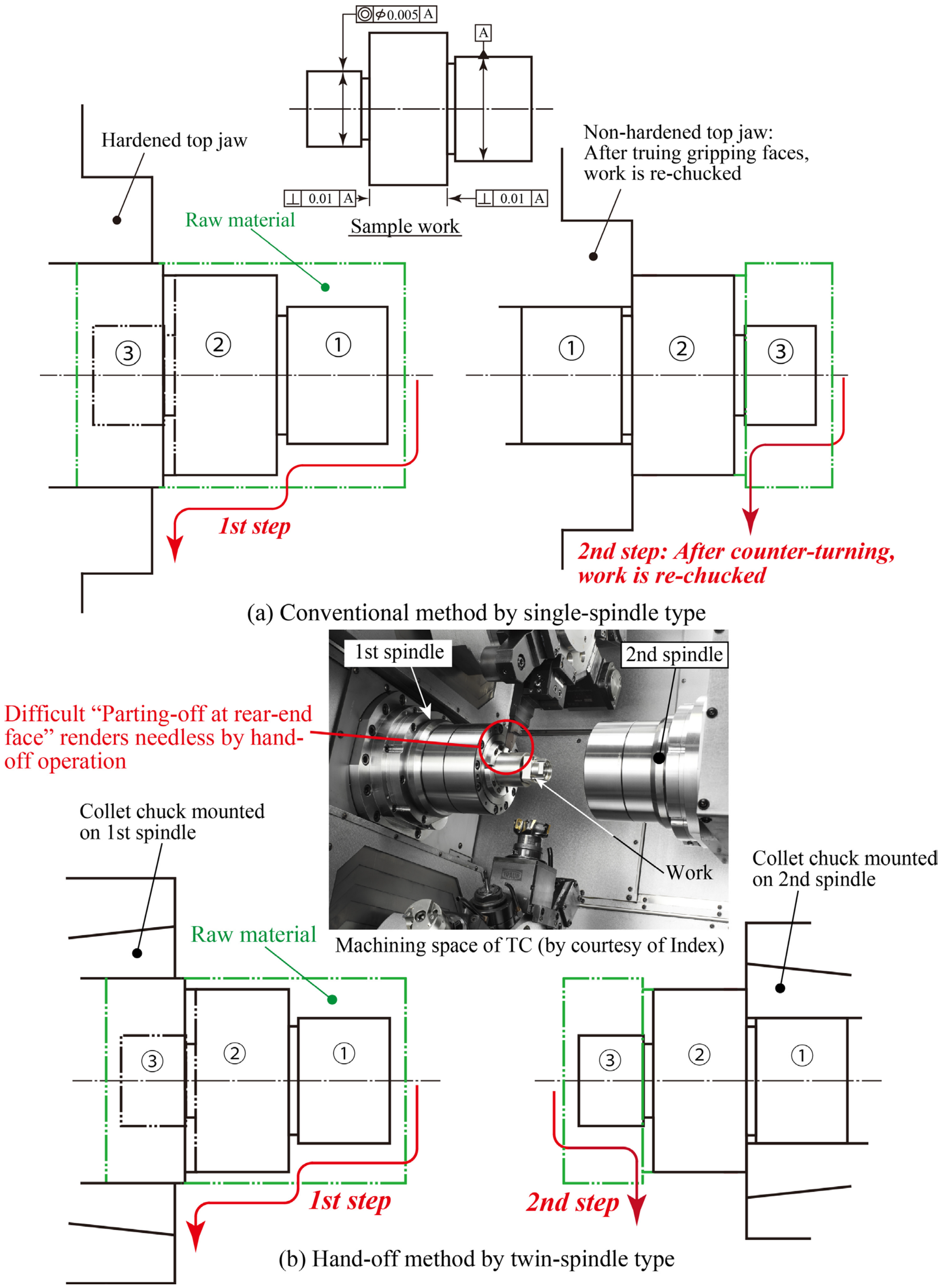
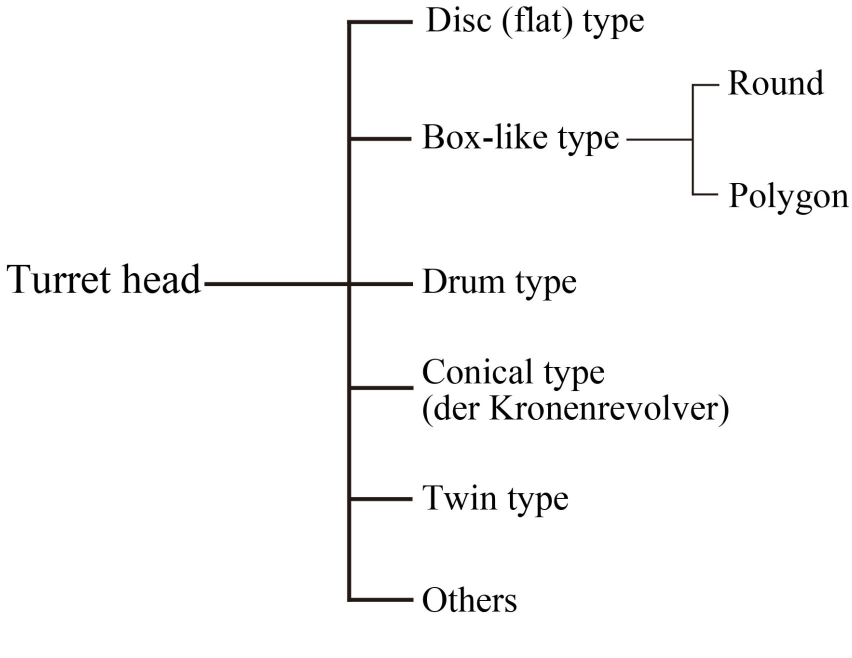


Fig. 3.5 Comparison of beneficial use of twn-spindle with conventional turning by single-spindle

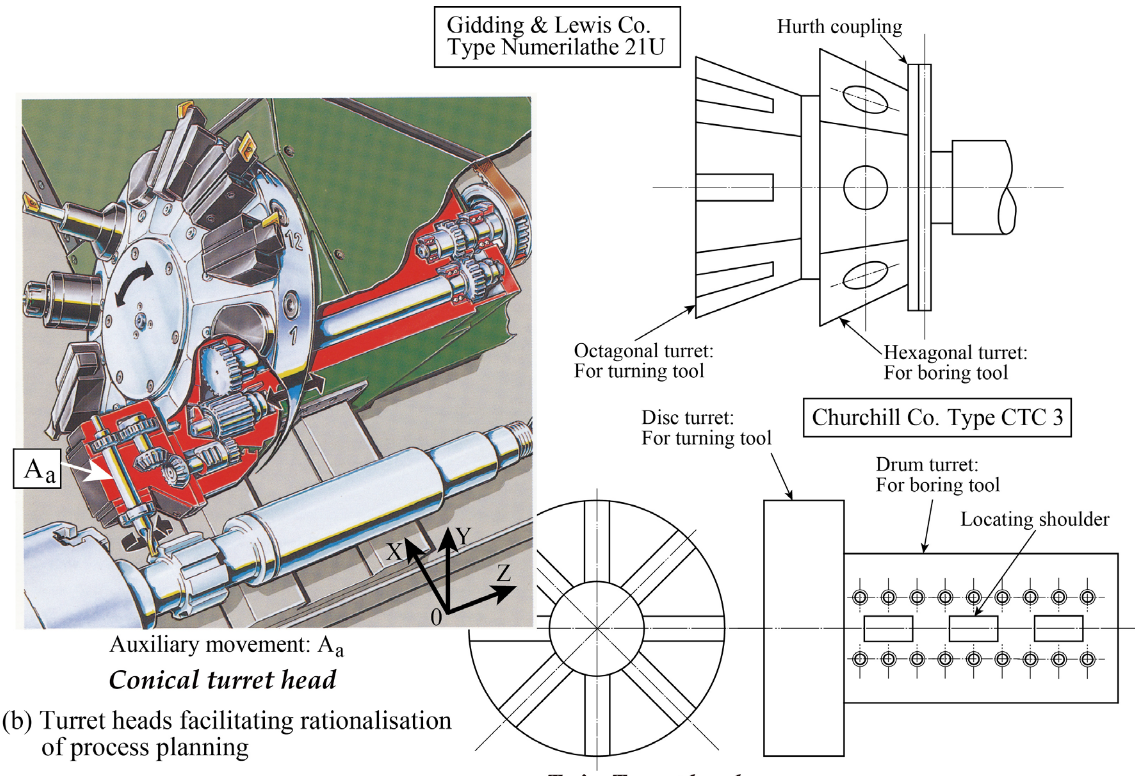
In principle, the work should be finished its one branch at 1st machining, and then furthermore finished the other branch at 2nd machining, after truing the jaw and re-chucking in the case of TC of single-spindle type. Of course, in the case of requiring much better accuracy, we must use the jig.

In contrast, we can use the “Hand-off” operation after 1st machining, and duly finish the work by the other main spindle at 2nd machining, provided that the concentricity between both the main spindles is within the allowable accuracy, and also the collect chuck with higher grasping accuracy should be employed. Importantly, even in TC of single-spindle type we need not re-chucking when employing the innovative cutting tool as will be discussed later.

As will be clear from the above, CAPP depends furthermore upon the structural configuration of the turret head including tool bracket and tool block to some extents, and duly the number of turret heads available within the machining space. Figs. 3.6 (a) and (b) show various configurations in turret head, and of these, both the “Twin type” and the “Conical type (Kronenrevolver)” may function to produce valuable process planning, although it is difficult to find their effective applications to the practice. In fact, the former increases considerably the flexibility in tool layout, and the



(a) Classification of turret head



Conical turret head

(b) Turret heads facilitating rationalisation of process planning

Twin-Turret head
(Based on sketch by Ito, at IMTS Chicago, 1982)

Fig. 3.6 Various structural configurations in turret heads

latter can simplify tool mounting on the turret seat. More specifically, in the conical type, the turret seat is declined to the main spindle axis, and thus the tool axial direction can be positioned either along or perpendicular to the main spindle axis after indexing it to the cutting position.

Figure 3.7 shows a mill-turn, i.e., a variant of TC, with multiple turret heads in comparison with that with milling head. Importantly, it is said that both mill-turns have the same capabilities; however, such a discussion was carried out without indicating the process sheets for the work shown also in Fig. 3.7. As can be readily seen, there are a considerable number of ***research subjects aiming at the rationalization of process planning by the number and allocation of turret heads within the machining space, configuration of the turret head and tool bracket, tool layout for a tool seat (see Fig. 3.6), and so on;*** however there have been no research activities, and there remains something to be seen.

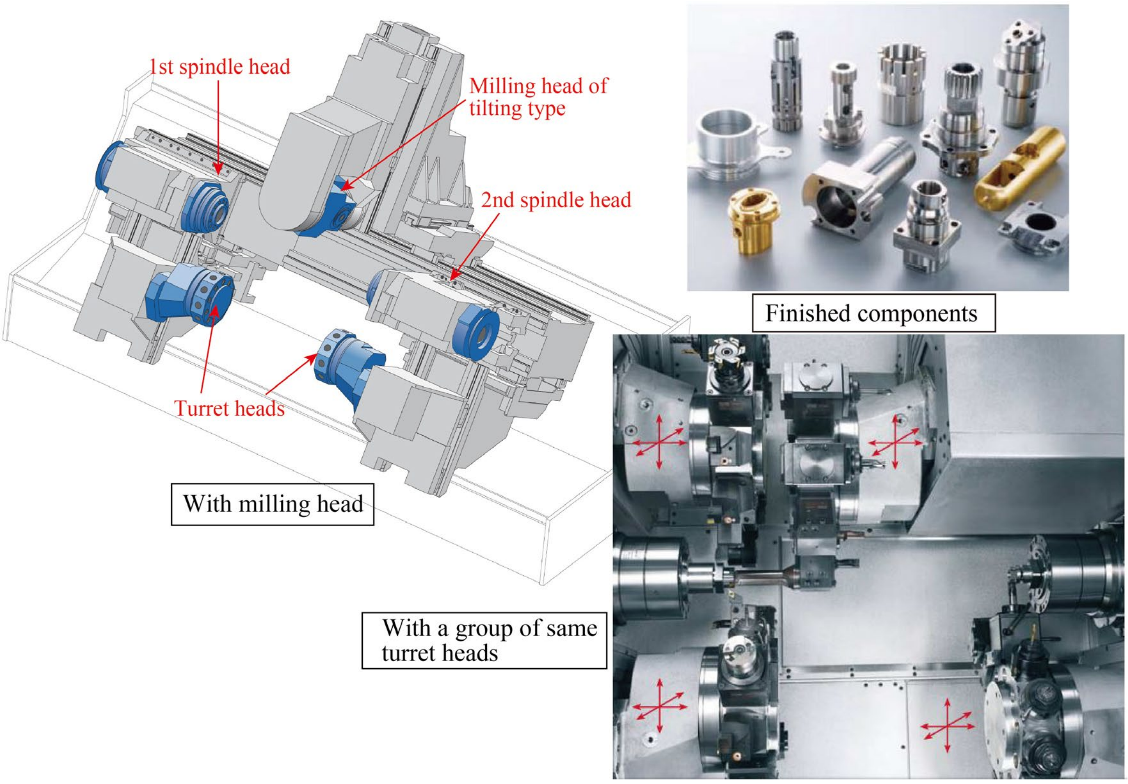


Fig. 3.7 Two representative mill-turns capable of machining same part family (by courtesy of Traub, 2009)

To this end, we must be furthermore aware of the following. In the effective use of “Hand-off” operation in machining with better accuracy, another primary concern is to be the thermal stability of the machining space in full reality. From such a point of view, the twin-spindle of opposite mounted type is desirable as illustrated in Fig. 3.8. More specifically, the heat flow may be circulated duly and thoroughly across the whole machining space by oppositely mounted both the spindle heads. As a result, we can expect conceptually the thermally stable machining space, and such a noteworthy design idea is credited to Hüller-Hille in 2002. ***At present, Index applies such a design idea to TC and merchandizes the corresponding machine as shown in Fig. 3.9; however, such a thermal stability has not been investigated and verified so far, although growing its importance more than ever before.***

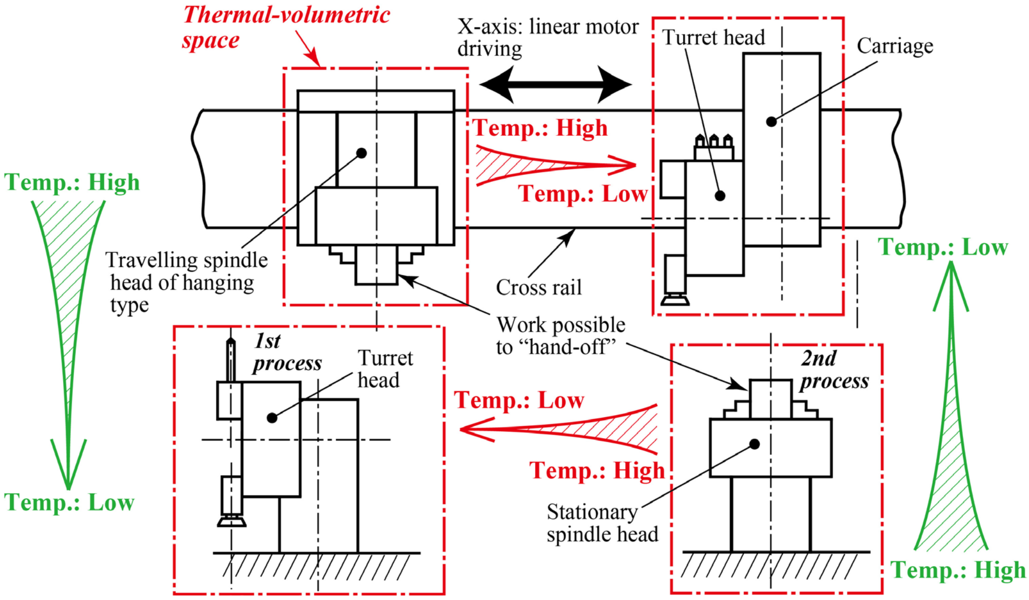


Fig. 3.8 Vertical turning machine of twin-spindle type possible to actualize thermally stable machining space (Type DVT of Hüller Hille-brand, 2002)

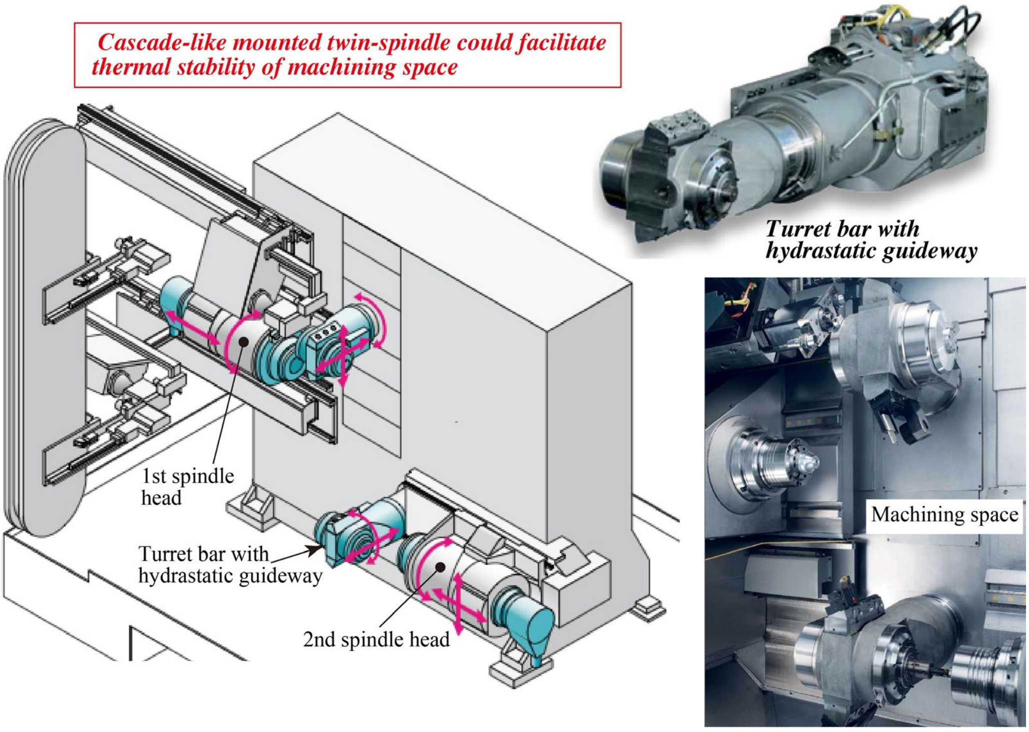


Fig. 3.9 Mill-turn of opposite allocated twin-spindle type possible to facilitate thermally stable machining space - Type R 200 of Index-make (Twin-quinaxial control type)

3.2 First-hand View for Innovative Attachments and Tools

At present, there are two representative methods within the innovative attachment and tool, i.e., those with modular system and of function-integrated type (combination system). Of these, the function-integrated type is handy as compared with the modular system in practice.

3.2.1 Attachment and tool with modular system

In retrospect, the chuck and cutting tool of modular type were once prevailed with the advance of FMS and FMC (Flexible Manufacturing Cell) in 1980s. For example, ACC (Automatic Chuck Changer) and AJC (Automatic Jaw Changer) were employed within FMC for turning together with cutting tool of modular type. As were expected beforehand, these modular attachment and tool achieved considerable benefits; however, we needed to install the transportation equipment within FMC.

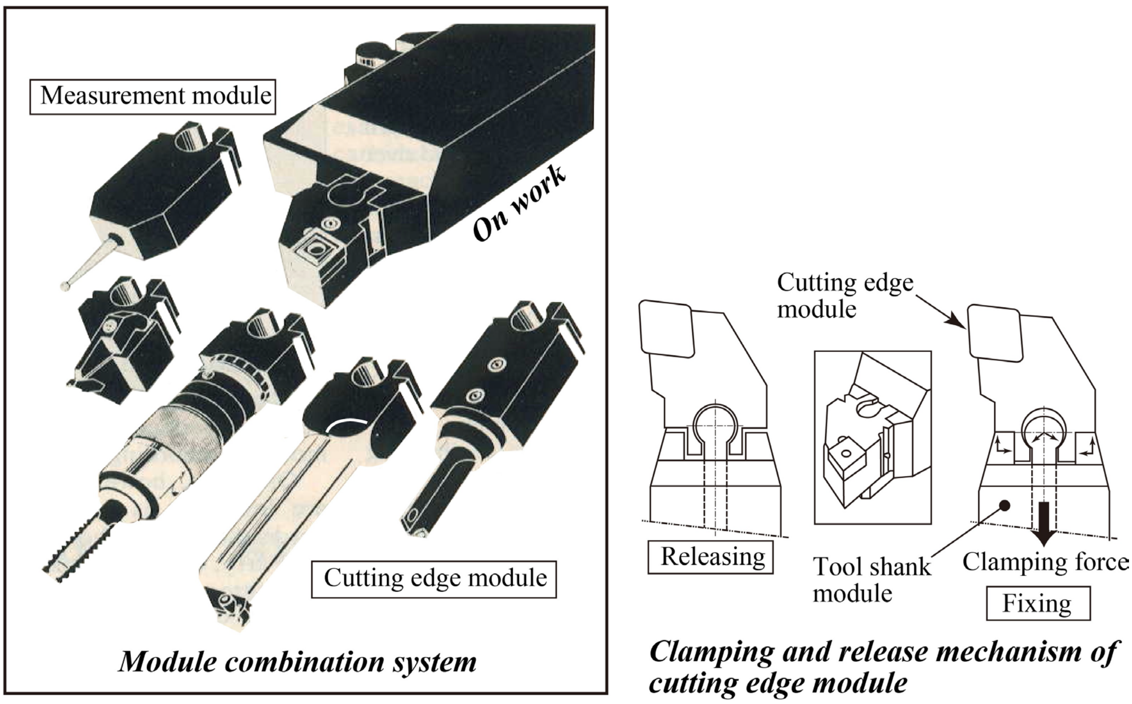


Fig. 3.10 Block tooling system
- A variant of modular tooling systems (By Sandvik, 1980s)

Figure 3.10 reproduces a modular tooling system of Sandvik-make in 1980s. In due course, the cutting-edge module was contained within the tool magazine of drum type, and in accordance with the machining requirement, the corresponding cutting-edge module was transported from the tool magazine to the machining space by the traveling robot. Obviously, the flexibility of the tool layout increased considerably, whereas the preparatory time increased.

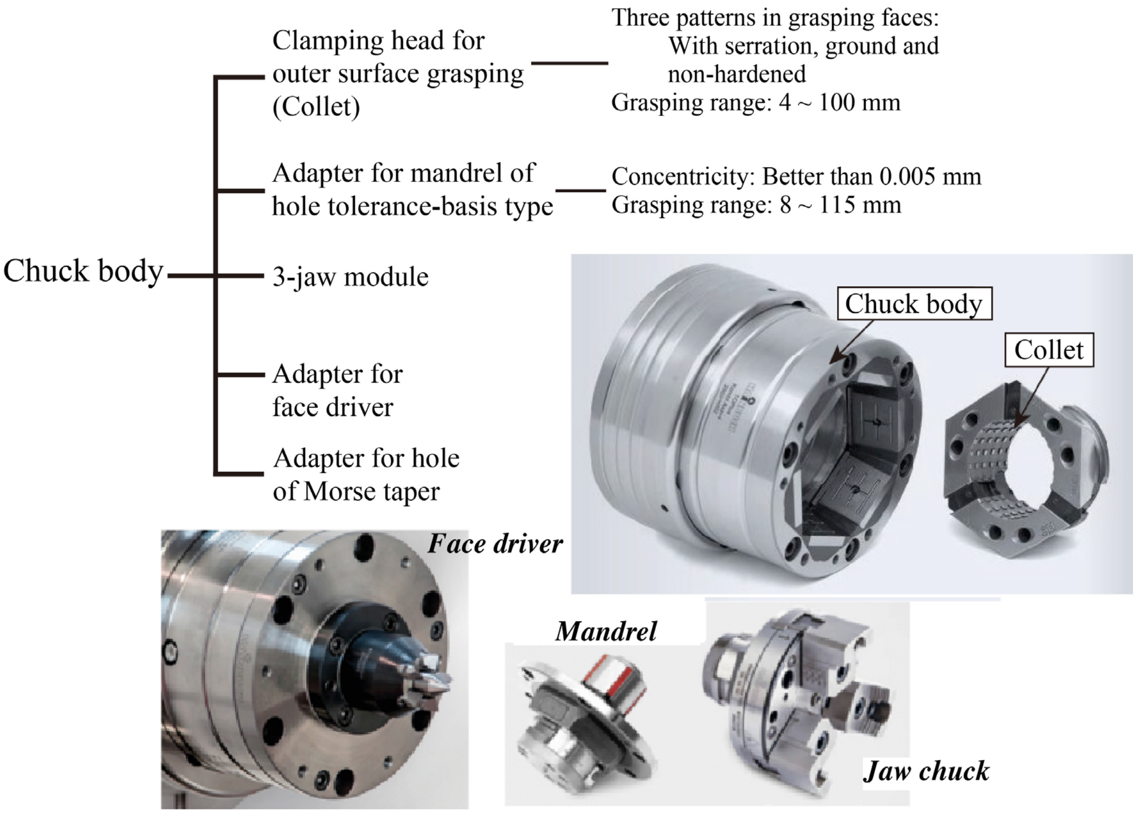


Fig. 3.11 An innovative collet chuck of modular systems (by courtesy of Hainbuch, 2016)

As will be clear from the above, the modular system is, in general, not so effective from the viewpoint of the rationalization of process planning even now. For example, Fig.3.11 shows the most advanced modular chuck of Hainbuch-make, which is applicable to various work grasping ranging from the jaw and collet chucks, through mandrel, to face driver. Figs. 3.12 (a) and (b) show furthermore modular tooling system, which can be characterized by using, in general, the “cutting-edge of quick changing type“, and also the “Buttress Thread” to connect the cutting-edge to the tool shank module with secure tightening. Surely, these tooling systems reinforce indirectly the rationalization of process planning by their flexibility in tool layout. ***Of***

special notes, it emphasizes that one of leading research subjects is to seek a preferable application of the modular attachment and tool to rationalization of process planning.

(a) Modular tooling system of cutting edge-oriented type around 2015

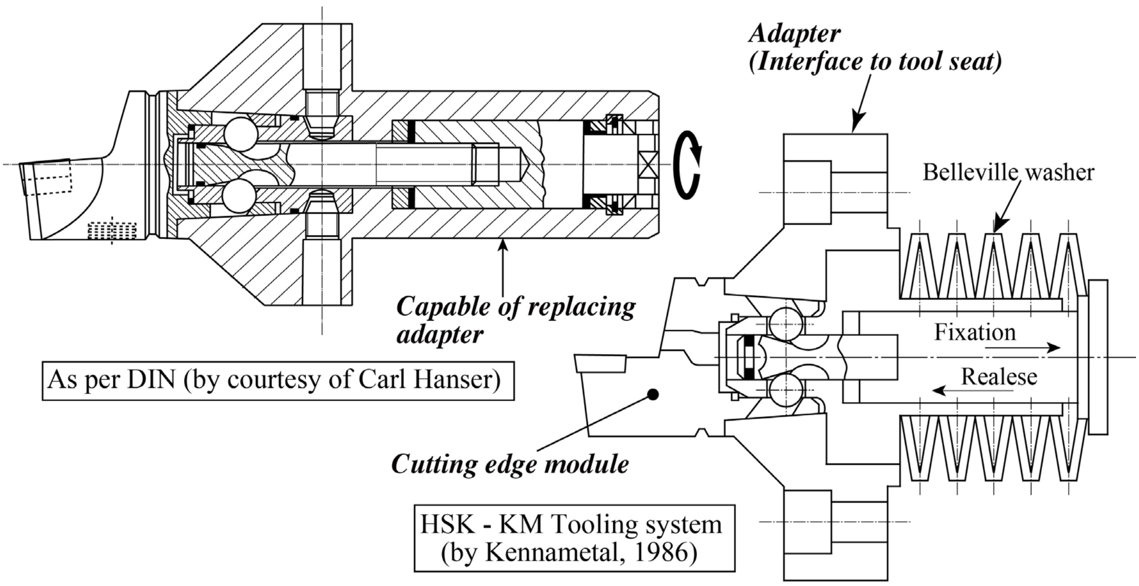
(b) Cutting edge of quick changing type

Fig. 3.12 Modular tooling system and cutting edge of quick changing type around 2015

Importantly, the turret head can facilitate the primary form-generating movement and to reinforce its flexibility, the modular tool layout is very effective. Figs. 3.13 (a) and (b) show two representative cutting-edge modules and as can be readily seen, these modular tools employ the cutting-edge module only, and thus very handy together with ensuring higher rigidity than those of modular tool in general.

There have been however no research activities for the effective application of such modular tools to the rationalization of process planning. More specifically, at issue is to what extent the tool layout with modular system is applicable to the machining requirements of a part family and its variants. In this context, we must be furthermore aware the validity of the taper connection of the cutting-edge module, i.e., either cylindrical or polygonal type (see Fig. 3.13(b)), from the viewpoint of process planning.

In general, it is said that the mounting seat of polygon type is superior to that of cylindrical type in the positioning accuracy and rigidity; however, we have not had reliable and quantitative evaluation data so far.



(a) Cylindrical taper connection

Type PSC63, Kennametal-make

Type HSK A63 WH, Iscar-make

(b) Polygonal taper connection

Fig. 3.13 Modular tooling system of HSK type

To this end, it emphasizes that ***another facing issue in the modular tooling is to design a desirable gang tool instead of mounting a single cutting tool*** on a tool seat in the turret head. In other words, in TC with multiple turret heads, single cutting tool with tool bracket mounted on one tool seat of turret head has become very popular. It is however preferable to use the gang tool when producing the process planning with economic efficiency, although such a trial has been very seldom so far. Typically, we may be in fruition such tooling systems by scrutinizing the tool layout in the automatic turret lathe and multiple-spindle automat in the past as shown, for example, in Fig. 3.14.

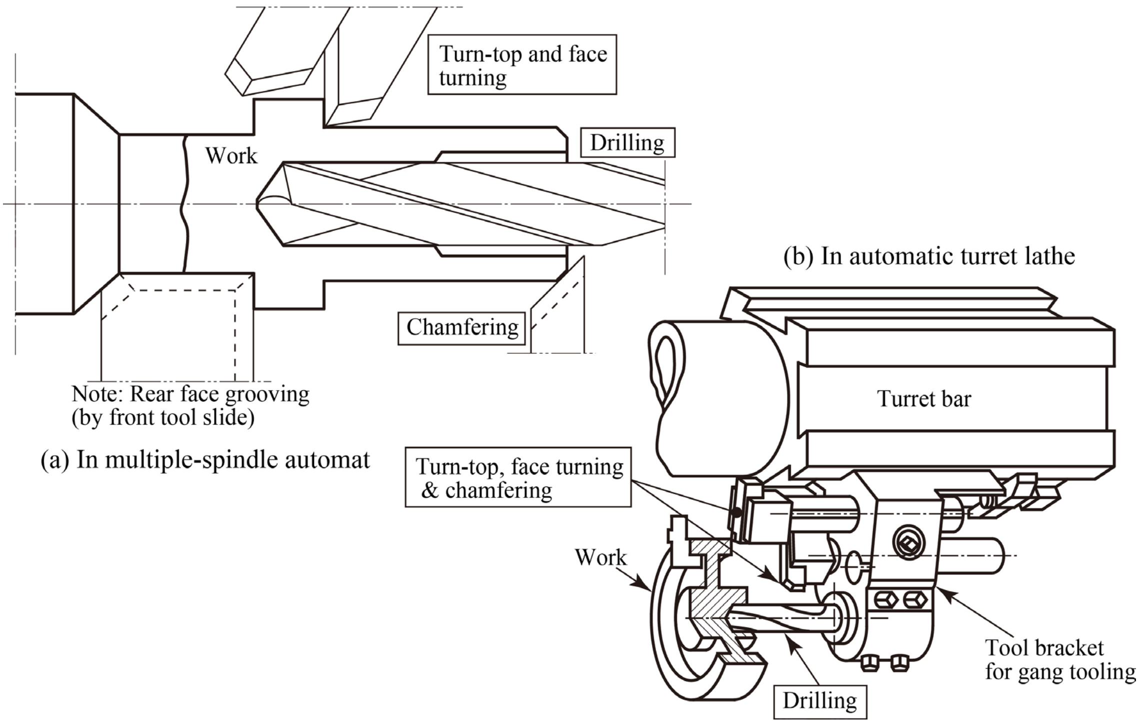


Fig. 3.14 Integration of various machining methods within one process

3.2.2 Attachment and tool with function-integrated type

In fact, the attachment and tool with modular system are effective indirectly on the rationalization of process planning, whereas those with function-integrated (combination) type give us directly very beneficial effects on process planning.

Typically, Fig. 3.15 shows two representatives of the combination chuck and pendulum chuck for thin-walled work. The combination chuck consists of the face driver and jaw chuck, and first the work is held by the face driver to finish the grasping surface while the jaw is in the retracted position. Then, the work can be held by the jaw to carry out turning for necessary form-generation. In contrast, the latter is not of combination type, but renders the jig useless, resulting in the reduction of preparatory work.

Within the combination tool context, there are two typical types, both of which can be produced various shapes by one-hit feeding, resulting in the considerable reduction of the machining time. In principle, one integrates several tools for the different machining purposes within a monolithic tool as a whole such as shown in Fig.3.16, where the drill with chamfering and

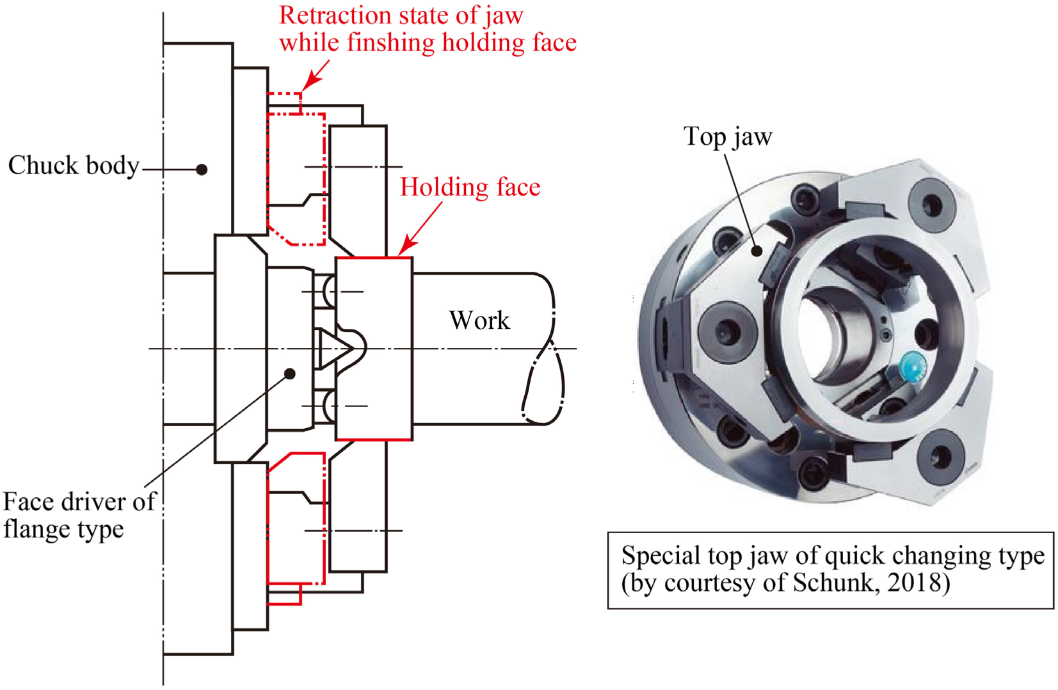


Fig. 3.15 Combination and pendulum chucks for rationalization of process planning

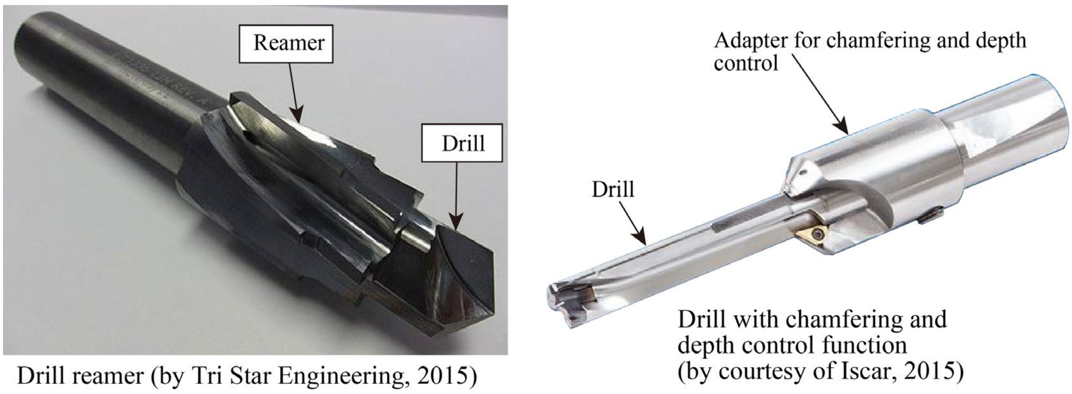
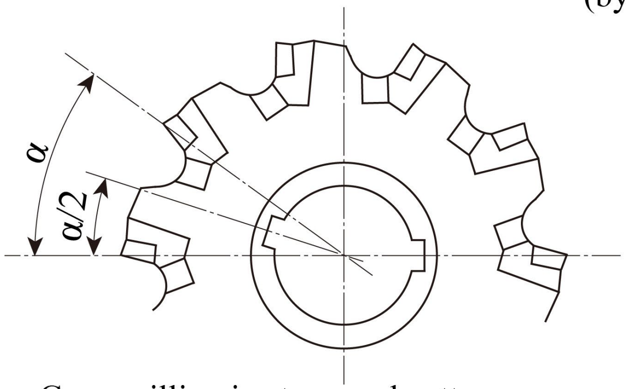


Fig. 3.16 Examples of combination tool

depth control functions can generate the drilled hole together with chamfering the entrance of the hole. The other is of gang type consisting of the same tools as shown in Fig. 3.17, where the boring bar for stepped hole is very popular from the past, and where the staggered gang milling cutter is newly commercialized. Of note, the staggered gang milling cutter is very interesting, because of facilitating the suppression of chatter vibration by shifting the adjacency cutting edge at certain angle. Importantly, there is a combination of drilling and boring, and also gang tooling as shown in Fig. 3.18.

Typical boring bar for stepped hole
(by courtesy of Mapal, 2018)



Gang milling in staggered pattern
mounting (by courtesy of Sandvik, 2015)

Fig. 3.17 Gang cutting tools

Fig. 3.18 Multiple-spindle head for drilling and boring
(by courtesy of SU-matic, 2015)

As will be clear from the above, we can expect the considerable rationalization of process planning by using the combination tool, and such tools grow duly their importance almost daily. Of special note, Fig. 3.19 shows the most advanced boring tool, which is a synergy of modular and combination types and for machining the component of the aircraft and motorcar. Importantly, this tool can be characterized by its heavy swarf removal, i.e., double volume than that obtained by the conventional tool, and in addition, has the following marked features.

(1) The slot drill is located at the center of the tool, and around it the face milling cutter with staggered-tooth arrangement is mounted. As a result, the radial component of the cutting force acting on the milling cutter can be counter-balanced, resulting in that the resultant cutting force can direct only to the axis of the main spindle.

(2) The cutting-edge module can be located by the taper and flange connection, which results simultaneously in the higher positioning accuracy and rigidity.

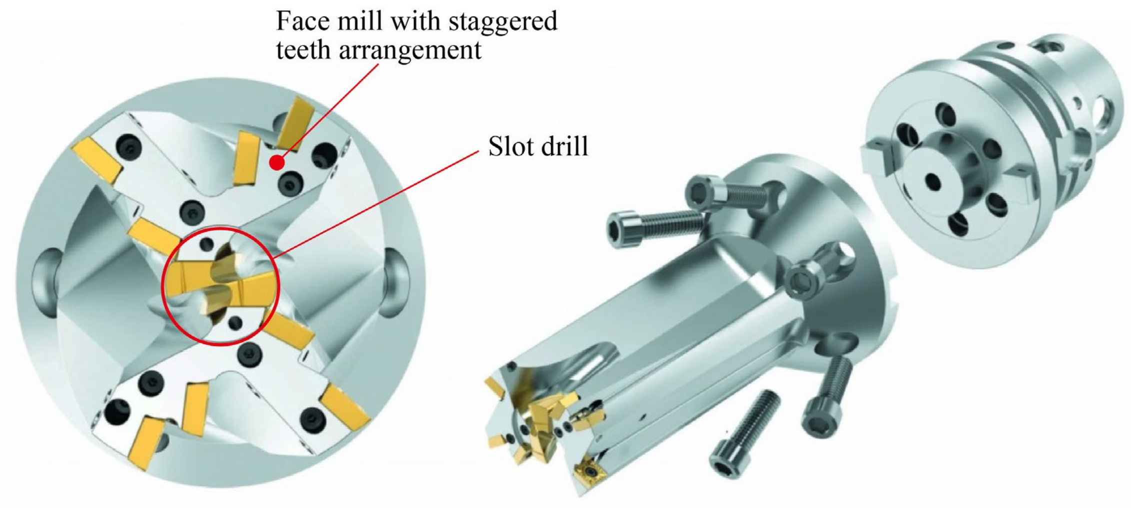


Fig. 3.19 Boring tool of modular and combination types
- Type FBX of Kennametal-make (patented, 2021)

3.2.3 Innovative improvement of conventional tools

As can be readily seen from Fig. 3.17, gang milling by a couple of grooving cutters with staggered arrangement, i.e., cutting edges with certain phase shift, can facilitates heavy cutting without the chatter vibration. In addition, a face mill of ISCAR-make appears as to be compatible with turn-milling better than ever before such as shown in Fig. 3.20. As exemplified by these, we may expect something noteworthy changes in process planning by improving the traditional and conventional cutting tool.

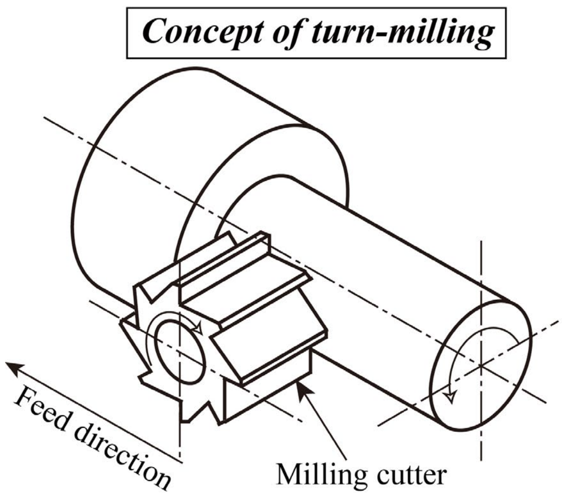
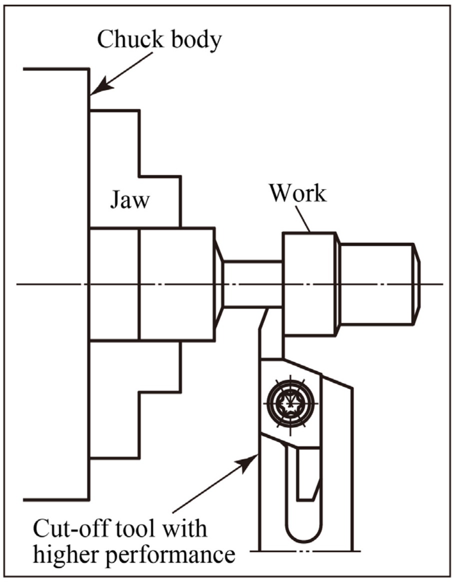


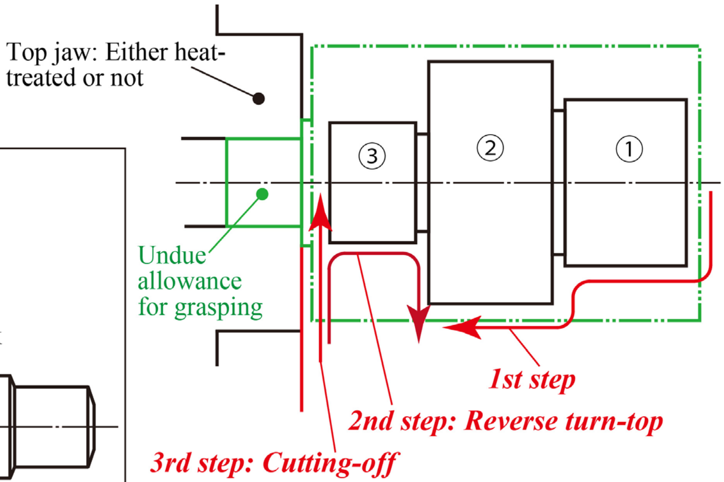
Fig. 3.20 Face milling cutter compatible with turn-milling
(by courtesy of ISCAR)

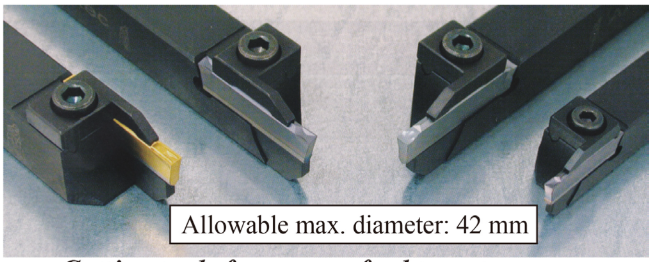
In fact, we can observe such a typical example as shown in Fig. 3.21, where an innovative parting-off tool plays excellent roles to generate a geometrical feature in the case of TC. In general, such a feature may generate by re-chucking the work; however, a parting-off tool with higher performance than ever before can travel to axial direction after in-feeding into the work, and generate the cylindrical shape by the reverse feed turning. Of note, Fig. 3.22 shows a reverse feed turning by the single-point cutting tool with special insert, which was for copy turning in the past.

In fact, there have been a handful of proposals for the innovative parting-off tool as shown in Fig. 3.23. For example, Iscar has merchandized a parting-off tool as similar as that of ARNO, the performances of which are as follows (Werkstatt+Betrieb, September 2021).



Innovative reverse feed turn-top and grooving (by courtesy of Dieterle, 2014)





Cutting tools for reverse feed turn-top, grooving and parting-off (by Applitec, 2014)

Fig. 3.21 Cutting processes of work with higher accuracy by TC of single-spindle type without re-chucking

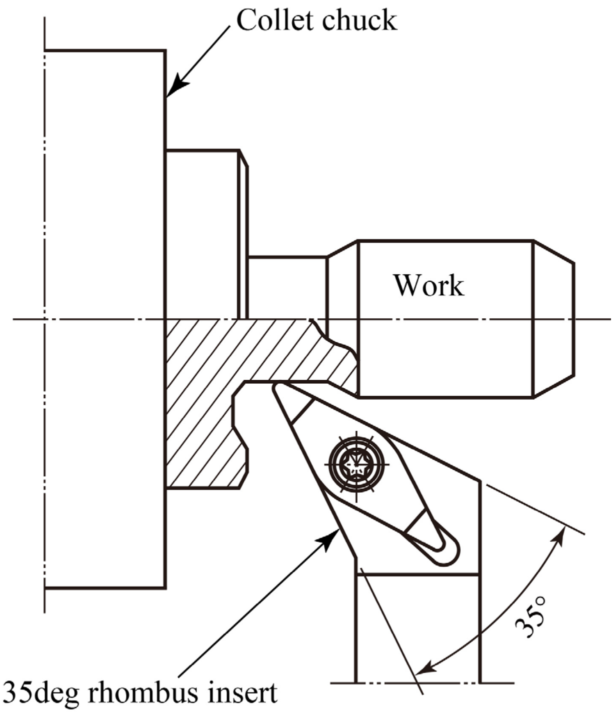


Fig. 3.22 Reverse feed turning by single-point cutting tool for copying lathe (by courtesy of Dieterle, 2018)

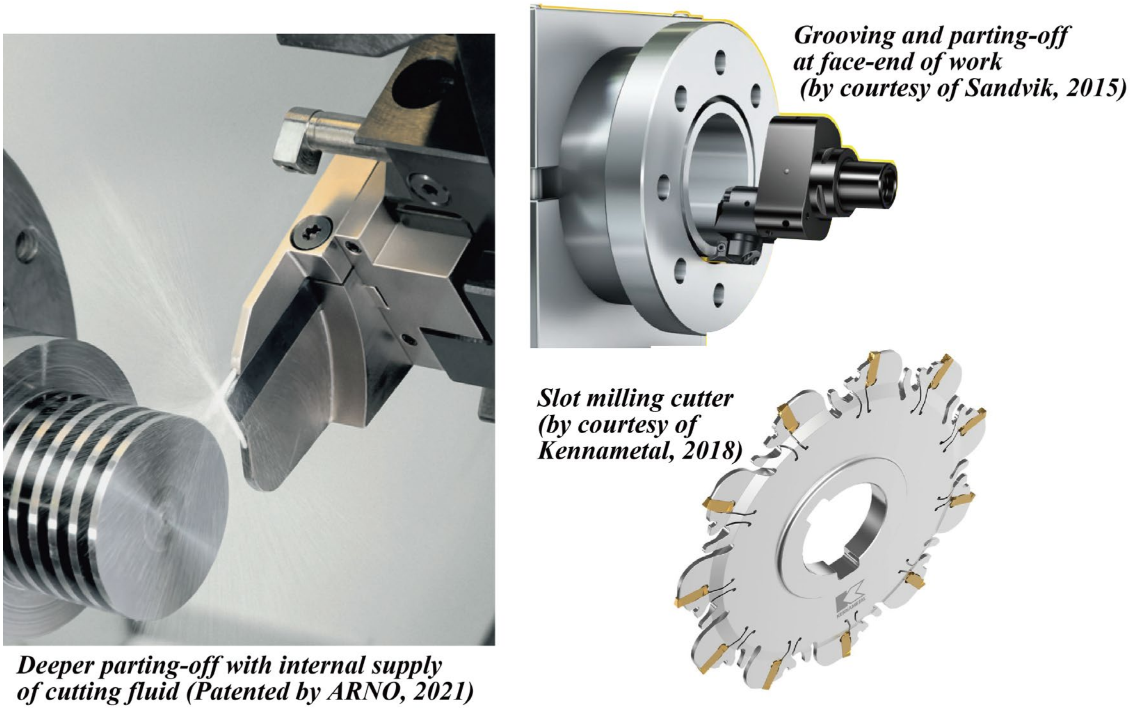


Fig. 3.23 Innovative parting-off and slot tools driving process planning to new horizon

(1) The depth of in-feed possible is around 20 times of cutting width, e.g., 40 mm in depth by tool with 2 mm in width.
(2) The parting-off speed is 2~3 times higher than that by traditional tool, and we need not finish turning to the parted-off face.

In addition to the parting-off tool, we can also see the marked improvement of the slot cutter (fluting cutter) as shown together in Fig. 3.23.

Conceptually, we can classify such improvements into bifurcation way: one can relevantly differentiate from others so far used. The other appears not to be important, because of its “Grass Root-like Improvement”; however, it affects considerably the rationalization of process planning as mentioned above. Of special note, we may discuss a “Scroll-free Turning” shown in Fig. 3.24 as a typical example of the former case. This turning method can be characterized by its helical located cutting edge made of PcBN, and also by its skiving-like cutting mechanism. Obviously, we may use it to finish the hardened seat for bearing and oil seal, and thus expect its large potentiality when using by TC with laser processing function.

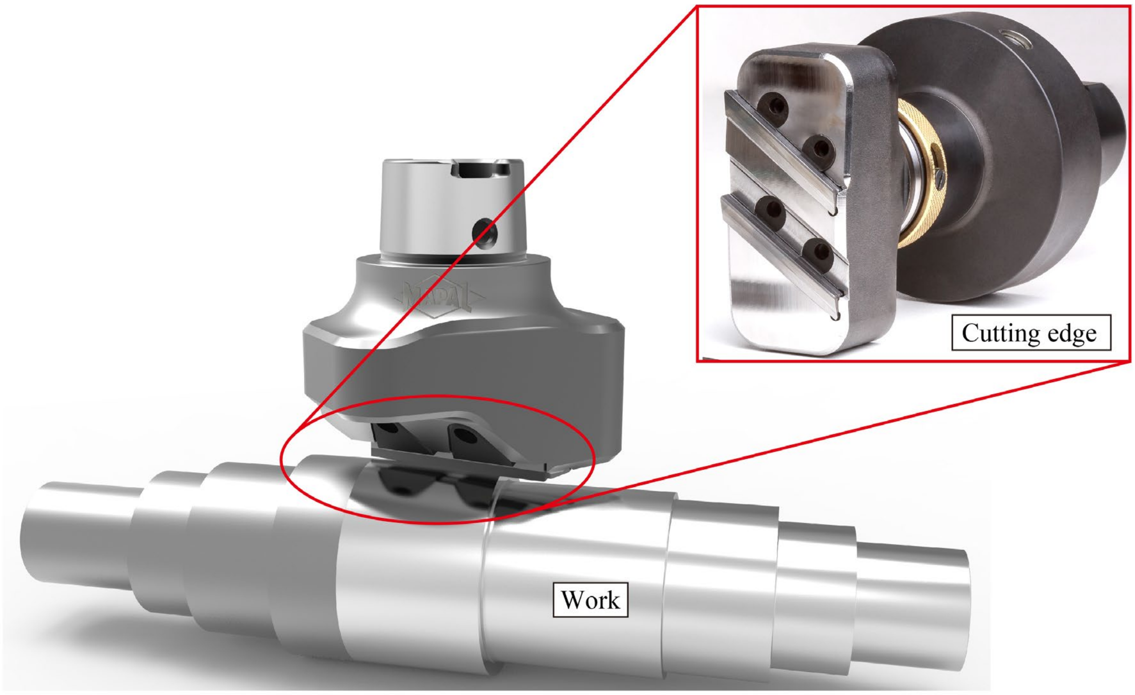


Fig. 3.24 Scroll-free Turning (by courtesy of Mapal, 2014)

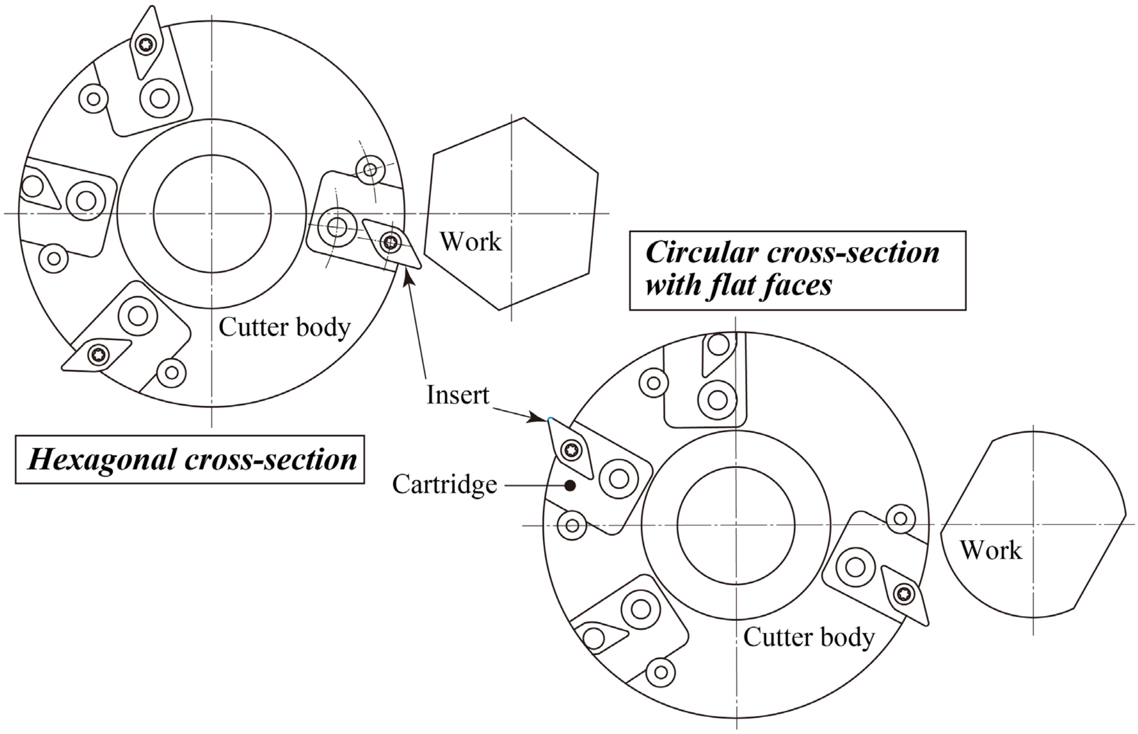


Fig. 3.25 Generation of shaft with non-circular cross section by polygon cutter (by courtesy of Dieterle)

Importantly, Fig. 3.25 shows another interesting improvement of the conventional turning by the rotating tool like the “Polygon Cutter”, in which the form-generating movement can be facilitated by the regulated relative rotation of the tool to the work. In fact, we can produce the flat face after finishing the cylindrical form while maintaining the rotation of the work.
Within the grass root-like improvement, we can suggest furthermore the effectiveness of the cutting tool with internal cutting fluid supply shown in Fig. 3.26 on the rationalization of process planning. In this tool, the major objective is to supply the enough cutting fluid to the cutting point together with expecting the breakage of the long-curled swarf. The long-curled swarf may induce the damage of the finished surface and cutting tool in certain cases, resulting in something unfavorable cutting environment.

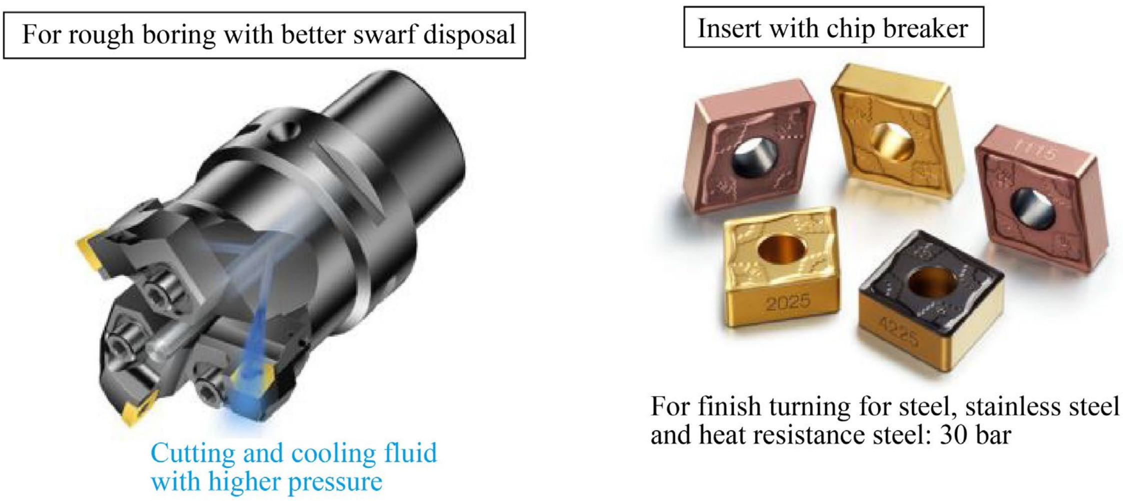


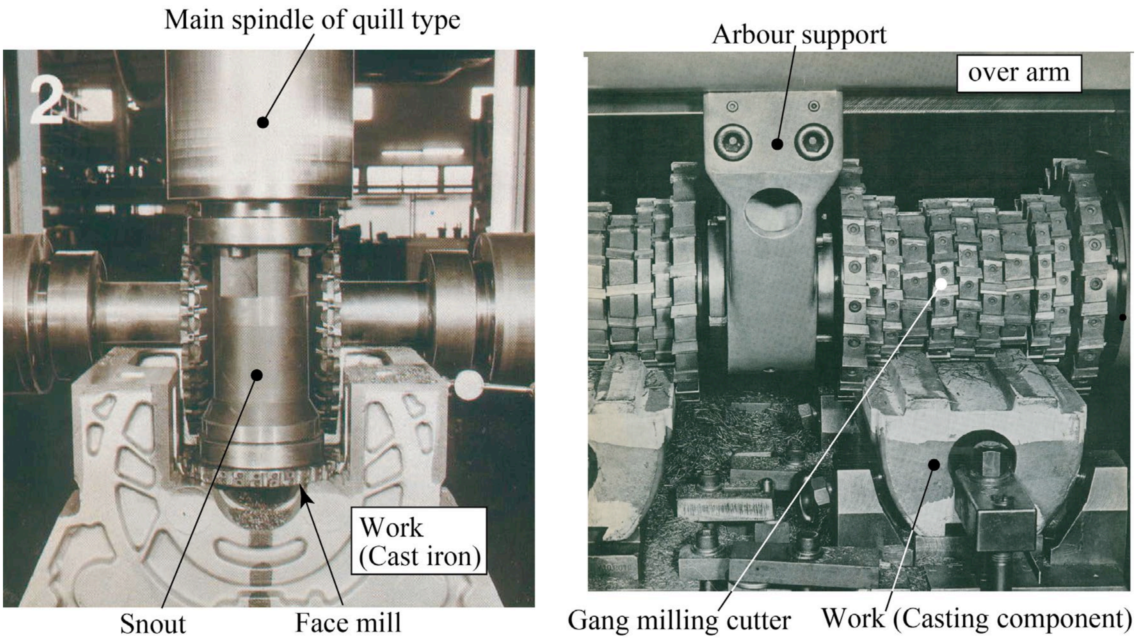
Fig. 3.26 Boring head and insert for internal supply of cutting fluid with higher pressure (by courtesy of Sandvik, 2015)

References

Ito Y. (2008) *Chapter 3 Description of Machine Tools*. In: Modular Design for Machine Tools. McGraw Hill, New York.
Fachartikel (3. September 2021) *Abstechen mit Hochvorschub*. Werkstatt + Betrieb.

Supplements

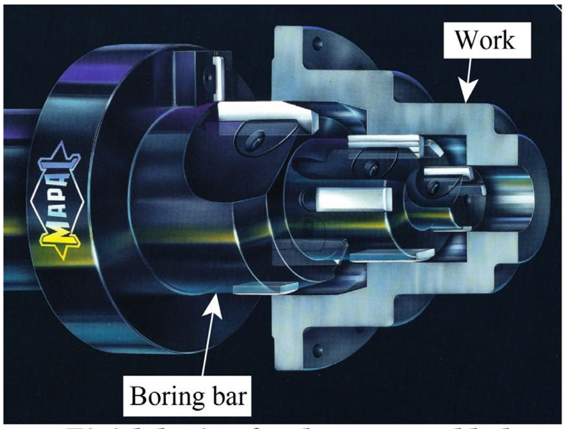
As typified by the gang milling cutter, we used to economize the machining process by means of the combination tools from the past. Thus, to understand what are differing features in the combination tools at present from those in the old day, some representatives so far used will be discussed in the following.



For planomiller by Heinlein, 1970s ***For horizontal milling machine by Heller, 1960s***

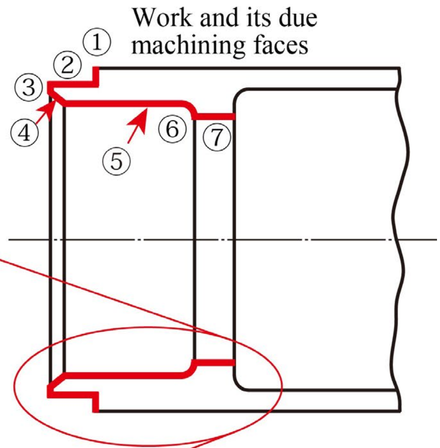
Fig. 3.S1 Form-generating movement by gang milling cutter

Figure 3.S1 shows two gang milling cutters for the traditional horizontal milling machine and planomiller, respectively. Importantly the former can be characterized by its secondary form-generating function, which can produce the stepped plane by one-hit feeding motion. Such a form-generating movement is also very popular in stepped-hole boring as shown in Fig. 3.S2, and as compared with Fig. 3.17, there are no new ideas, but only modernized.



Finish boring for three-stepped hole by boring bar of Mapal-make, 1987 at 7th EMO Show

Seven-face simultaneous machining by using "Microbore" in part, 1960s



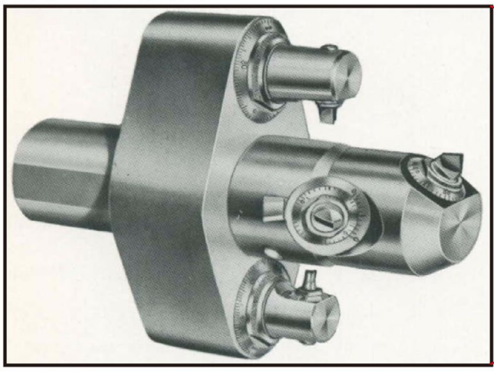
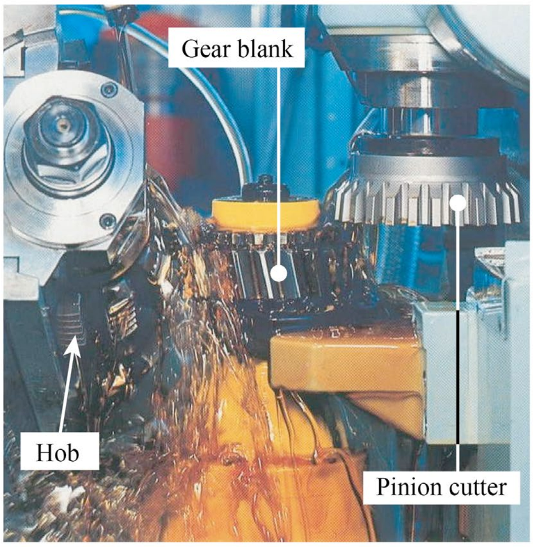


Fig. 3.S2 Stepped-hole boring by multiple-edge tools

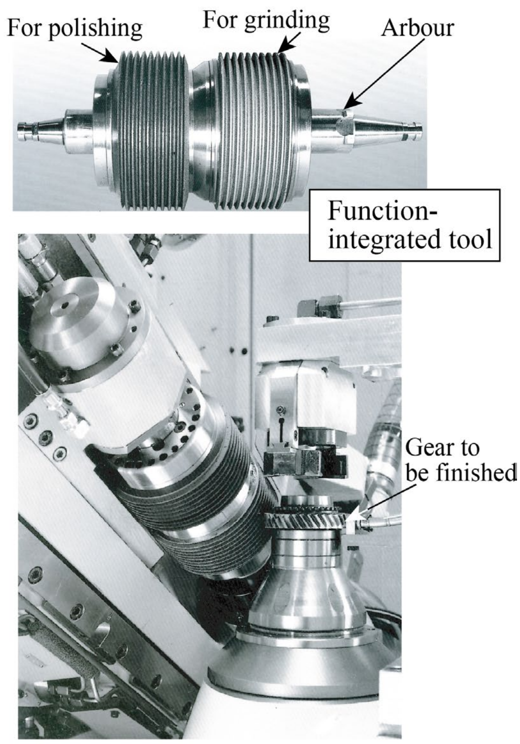
Even in the gear cutting sphere, we can observe the effective use of the combination cutting and grinding. Fig. 3.S3 shows the combination of gear shaping with gear hobbing, and furthermore a synergy of gear grinding and polishing. Obviously, these are very effective to shorten the preparatory work, and in that of Pfauter, we may expect the ease of cutting for the gang gear with adjacency gear of larger diameter.

Within the gear production context, we can remind such an interesting method for gear honing shown in Fig. 3.S4, in which the form-generating movement can be facilitated by the "three leave clover-like grinding wheel" and the "symphony of two rotating axes". In short, Technishe Universität Berlin proposed the original idea of this innovative gear honing and Fässler applied it to the practical use.

Summarizing, either the integrated or multiple-edge tool in the past aimed at the reduction of preparatory and machining time, and of course such aims are even now primary concerns.

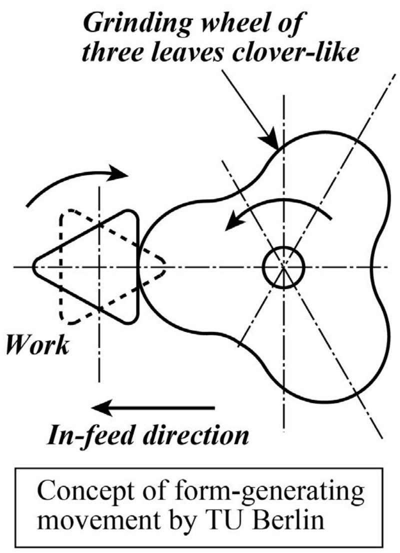


Integration of hobbing and pinion cutting - Pfauter, around 1990



Gear finishing by function-integrated tool - Liebherr, 1990

Fig. 3.S3 Integration of tools in gear production



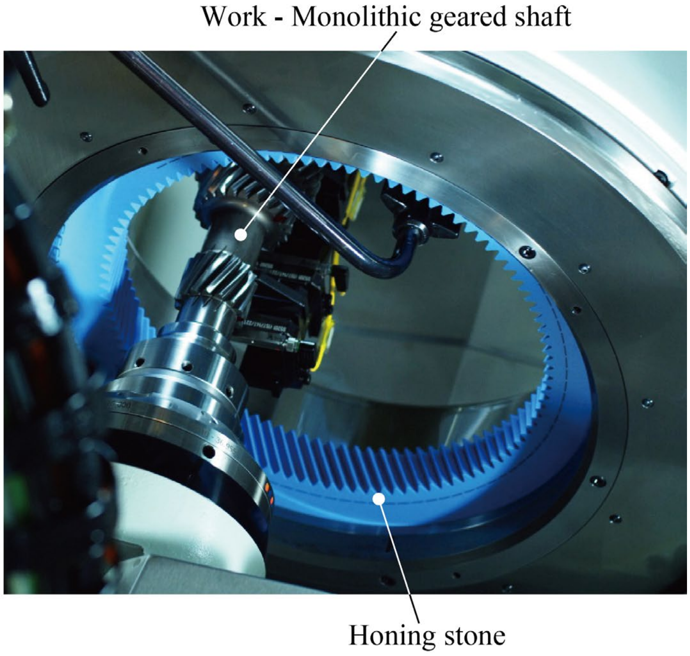


Fig. 3.S4 Innovative gear honing
- Type HMX-400 (by courtesy of Fässler, 2004)

Chapter 4 A New Concept for Process Planning and Its Variants - In Consideration of Thinking Ways of Experienced Process Planner and Innovative Form-generating Method

In accordance with the investigation into the past and present perspectives of CAPP, as already suggested in Chapters 1 and 2, at burning issue is to establish an effective linkage between the academic research and the practice. In fact, CAPP being investigated in academia is far from the practical application, because it is too much simplified process planning in practice. More specifically, the utmost hindrance is to convert the geometrical information on the part drawing without any difficulties into the machining-related information together with guaranteeing the "One-to-One Relationship" between both the information. Conceptually, all the CAPPs so far used in practice involve this hindrance by nature, and dare to say, even CAPP of expert system cannot overcome it, because of acute shortage of the knowledge database, which is the kernel of the expert system.

Within the "One-to-One Relationship" context, some research papers use "If-Then" rule; however, such a rule is not sufficient to solve the essential problem mentioned above. It is furthermore said that the knowledge database should be in fruition by the "Hierarchical, Modularized and Grouping Structure"; however, there have been no acceptable proposals for such databases.

A root cause of difficulties lies in the variety and complexity in the machining method to generate the same geometrical shape, i.e., geometrical feature or primitive volume (entity). In addition, we must consider, at least, the best availability of each machining method for the requirements in accuracy, capability, surface quality, and duly the machining time and cost.

Thus, an idea is to positively use the "Thought-Pattern of Experience Engineer" following to CAPP of flair type. In this context, it is desirable that we must simultaneously establish a conversion table for the geometrical feature to the machining method concretely available. Obviously, such a conversion table may be also available for the improvement of CAPP at present.

4.1 CAPP of Flair Type

In general, a crucial issue within CAPP is to establish the “One-to-One” relationships between the geometrical and the real machining features. It is thus natural that some researchers tried to visualize the thinking way and thought-pattern of the mature process planner by using the “Questionnaire investigation”, “Think aloud method”, “Eye mark camera method”, and so on. Simultaneously, they intended to incorporate such a thinking way within CAPP as one of decision-making function.

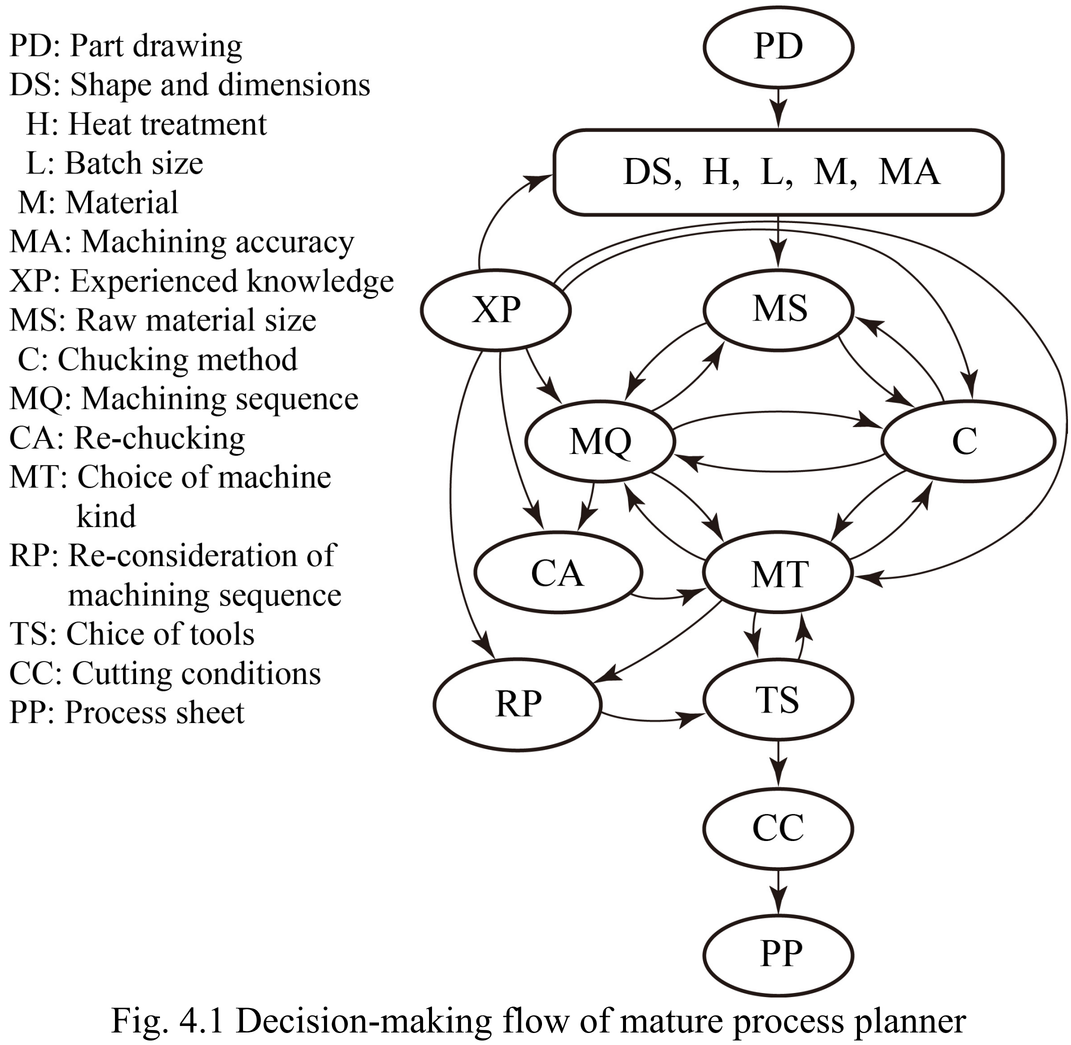


Fig. 4.1 Decision-making flow of mature process planner
- Visualization by directed graph

Figure 4.1 shows a directed graph in general, which can visualize a decision-making procedure of the process planner (Chen 1985). In fact, we can produce the directed graph by the “Face-to-Face Interview” or “Questionnaire Investigation”, where the core item (vertex with property description) is pre-given. More specifically, the subject should connect all the vertexes by the directed edges, which are necessary and inevitable to determine a vertex. Obviously, this is one of indirect visualizations for the thought-pattern of the process planner, and as can be seen, the circulating directed edges imply the cause of the “Ill-defined Problem”-like characteristic in process planning. In addition, we can observe several interesting matters as follows.

(1) There are certain numbers of variants in the directed graph depending upon the maturity, and also culture and mindset aspect of the subject, even when all the subjects belong to the same organization. In fact, two engineers belonging to the same organization produce different process plans with each other, and both the plans are acceptable, but not the upmost desirable one.
(2) The same subject shows a different directed graph from those obtained at another days. This means, the decision-making process is influenced considerably by the mental and physical conditions of the subject.
(3) The pattern of the directed graph changes to a great extent, i.e., less numbers of circulating edges, when providing the subject with such a part drawing, i.e., geared drive shaft, as a “Stimulus”. Fig. 4.2 shows an example, and we can see the strong individual dependence, although the circulating directed edges reduce considerably in general. In addition, the “Stimulus” induces a new vertex, i.e., GR, which plays certain important role to the pattern of the directed graph.

Of special note, we must be aware of it that the directed graph can be converted into the adjacent matrix, which is very convenient to the mathematical treatment.

Such a visualization by the directed graph is worth evaluating the decision-making of the process planner; however, it involves uncertainties caused by the leading question-like aspect to some extents, and thus Ihara and Ito (1991) proposed to use the “Eye mark Camera” to avoid such uncertainties.

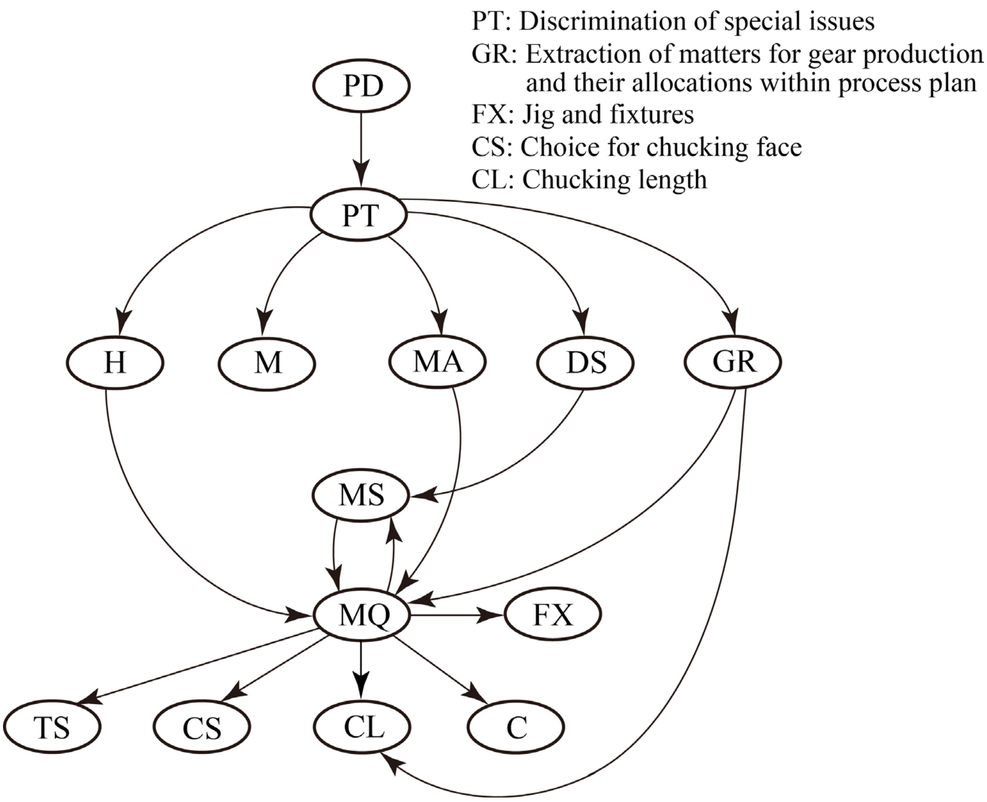


Fig. 4.2 Directed graph when providing part drawing

Fig. 4.3 illustrates the testing setup and shows an example of the test result. As will be clear from Fig. 4.3, the subject reads the part drawing projected on the large screen and simultaneously conducts process planning. While the subject produces the process plan, the eye mark camera records the movement of the eyeballs, i.e., moving direction and watching time at the special point on the part drawing, which may reflect indirectly the decision-making procedure of the subject.

Of note, the more numbers of the circles around a point, the subject is strongly interested in it, and also the longer the watching time, the larger is the recorded circle. Obviously, the latter means that the subject needs something necessary to understand the meaning of the watched point. Through the eye mark camera testing, we can first obtain to what attributes the subject is extremely interested in by investigating the earlier watching points immediately after starting the test. From a couple of such test results, it is clarified that the mature process planner uses a weighing principle to choose the priority order among all the attributes related to process planning.

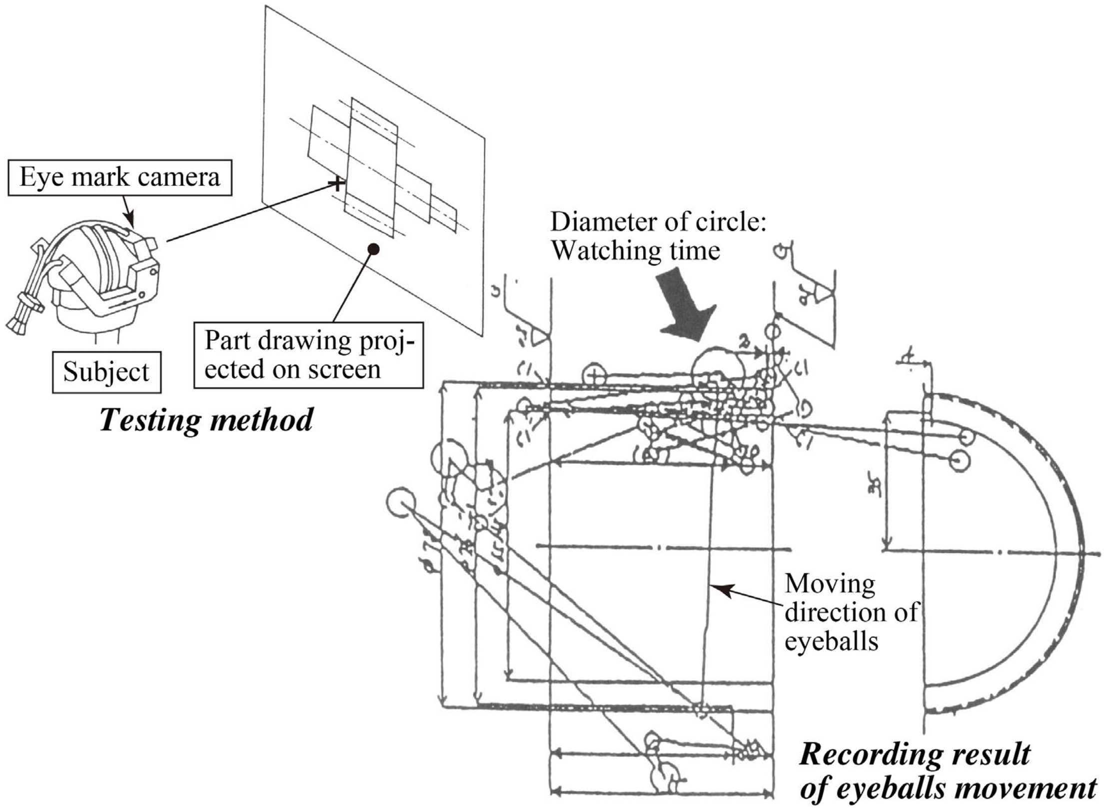


Fig. 4.3 Eye mark camera testing and a recorded result

More specifically, the mature process planner chooses several leading attributes from 1st to 4th such as shown Fig. 4.4, while conducting process planning. As a result, the process planner does not spend much more time to produce the process plan, which is, in general, acceptable with high quality. In contrast, nearly all CAPPs put, in general, the same weights on all the attributes, resulting in the time-consuming work.

In consequence, Ihara et al proposed an idea of CAPP of Flair type, in which the process planner discriminates several routes to produce the process plan, depending upon which leading attribute is in much more priority. Obviously, both the higher machining accuracy and the difficult-to-machining play the important roles, and thus we need to evaluate the difficult-to-machining.

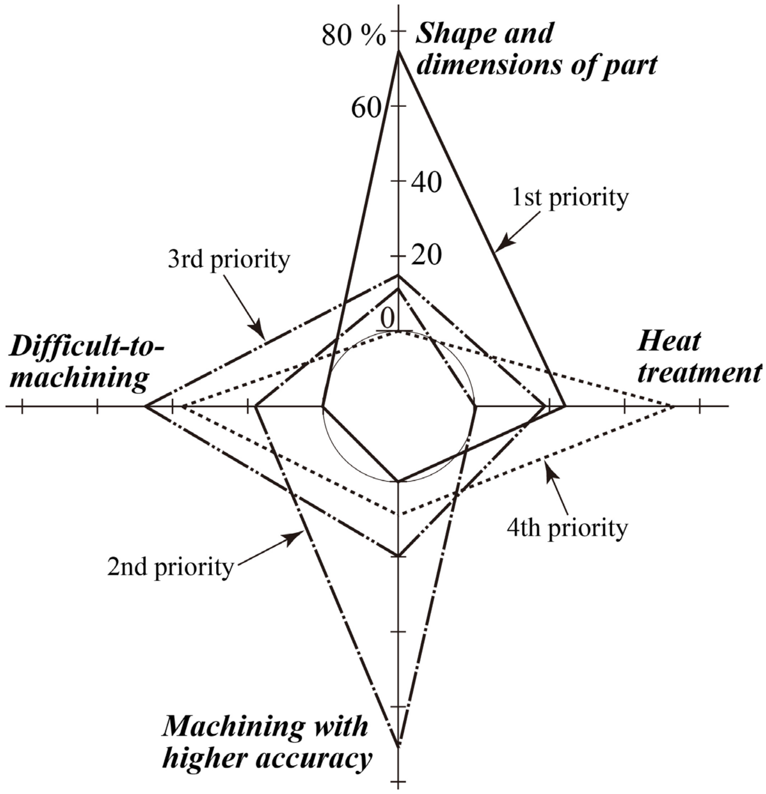


Fig. 4.4 Priority order of attributes on part drawing
in producing process plan by mature engineer

Thus, Ihara et al (1993) presume that the difficult-to-machining may be represented with the mutual relationships among the attributes related to “Thinkable Troubles in Machining” and “Possible Remedies for Troubles”. In consideration of the ease of mathematical treatments, such relationships are visualized by the directed graph as shown, for example in the case of the cylinder with thin wall in part, in Fig. 4.5.

After conducting a handful of trials, they can obtain a normalized directed graph by extracting the common patterns from the trial results as shown in Fig. 4.6, where we can find some attractive facts as follow.

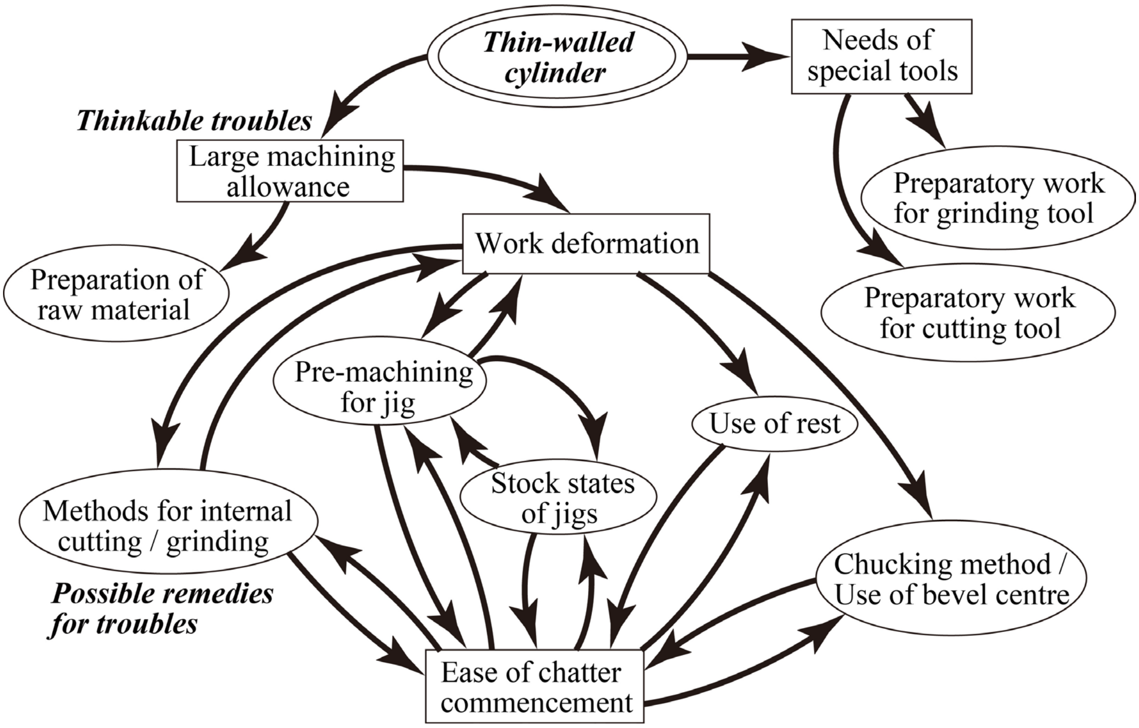


Fig. 4.5 Directed graph delineating "Difficult-to-machine" for thin-walled cylinder

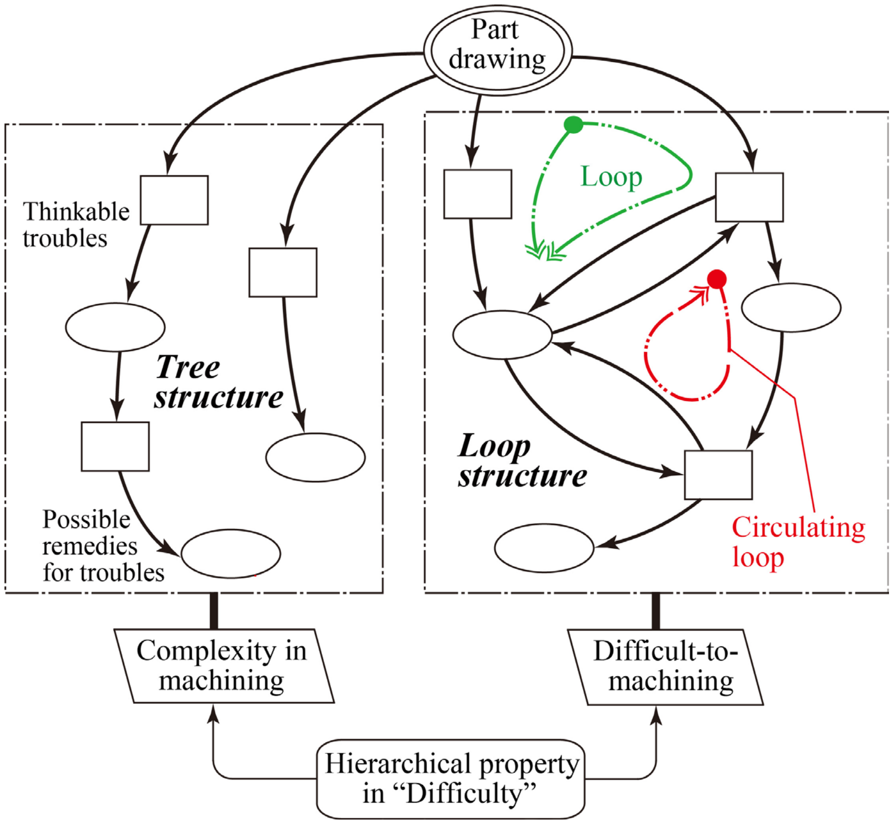
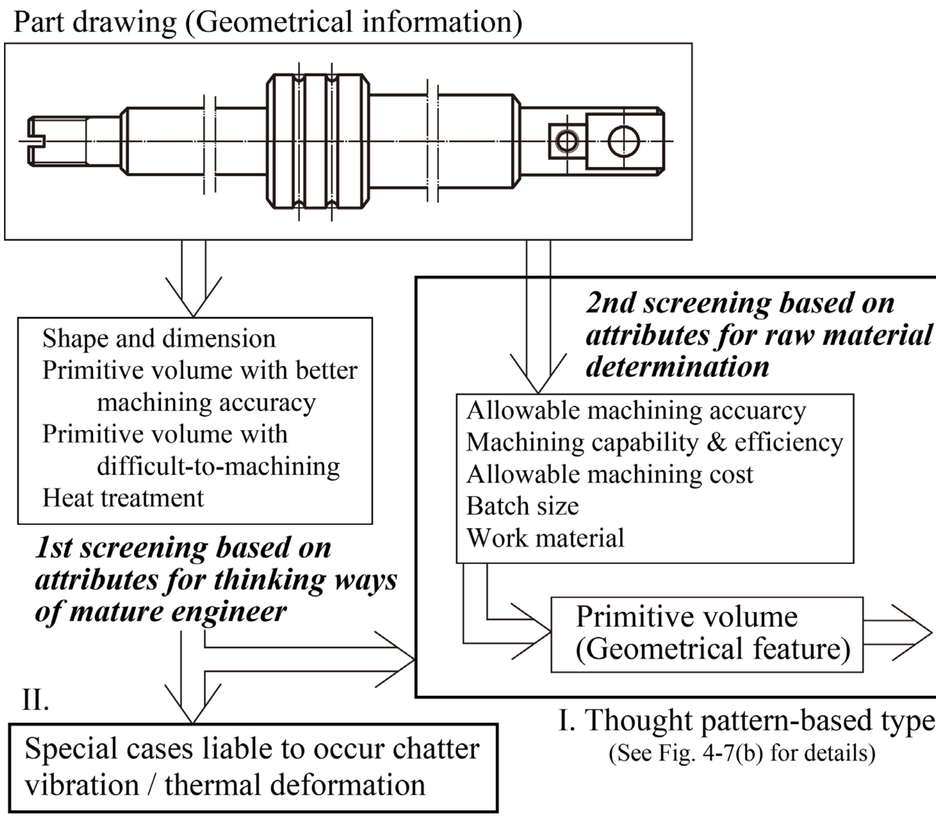


Fig. 4.6 Normalized directed graph to visualize "Difficult-to-Machining"

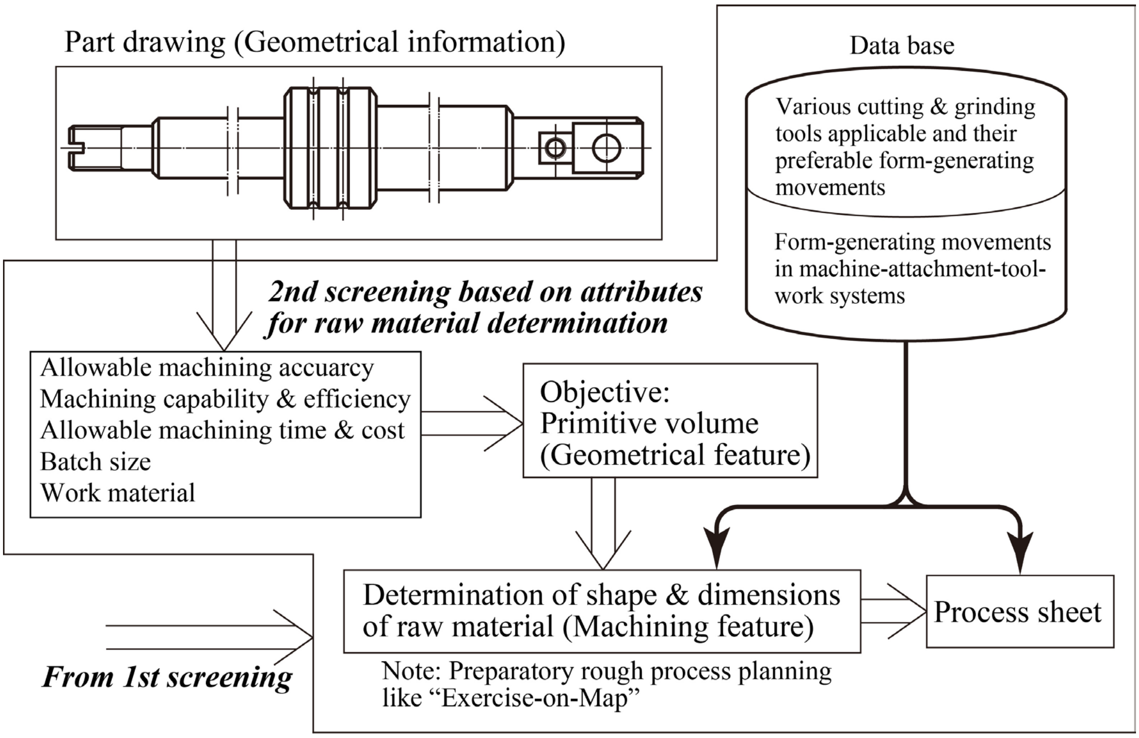
(1) The "Difficult-to-Machining" can be detailed into the "Complexity in Machining" and "Real Difficult-to-Machining", which can be visualized by the "Tree Structure" and "Loop Structure", respectively.
(2) The "Real Difficult-to-Machining" can be evaluated the number of "Loops" and "Circulating Loops", and the much more the latter, the "Difficult-to-Machining" increases much more.
(3) The "Complexity of Machining" does mean nothing even when it shows complicated flow. In fact, the mature process planner does not pay any attention to it.

4.2 A New Concept of CAPP, "Thought-pattern-based Type", and R & D Subjects for Its Establishment

Following to CAPP of flair type, thus, a concept for new CAPP may be based on the positive use of the "Thought Pattern of Experience Engineer", and Figs. 4.7 (a) and (b) are first-hand conceptual views of the proposed idea.



(a) Discrimination of first stage



(b) Details of "Thought Pattern-based" type

Fig. 4.7 Concept for CAPP of "Thought Pattern-based" type

In principle, the proposed idea consists of two cores, which can be characterized as follows.

(1) First screening phase based on thinking ways of mature process planner.

(2) Second screening phase based on thought pattern of engineering designer

Within Fig. 4.7 context, the mature process planner may decide whether the chatter vibration occurs or not, at glance the part drawing. ***To our regret, we have not visualized such a decision-making procedure of the mature engineer yet, resulting in R & D subject in future***. In general, the thin-walled work may induce the chatter vibration, and thus we need to reinforce such a geometrical feature with jig and fixtures, or with "Cut-off Rib" after due machining (Undue Rib).

As can be readily seen, a new idea may be in fruition by establishing two core functions, i.e., procedure for raw material determination and structural organization of database together with identifying the determinant.

Procedure for raw material determination

As will be easily imagined, we need various and wider knowledge to carry out the procedure for determining the utmost desirable raw material corresponding with the part drawing. For example, we must determine to use either the draw bar or forged cylinder, even when the material indicated on the drawing is the same. Of course, such a knowledge ranges from the properties of engineering materials in general, through form-generating movement of the machine body and attachment, to “Do-It-Yourself” tool. In principle, we must use the general knowledge about the engineering material regulated in the standards; however, such a knowledge renders often useless, and instead of them, we must rely on the factory floor-based data.

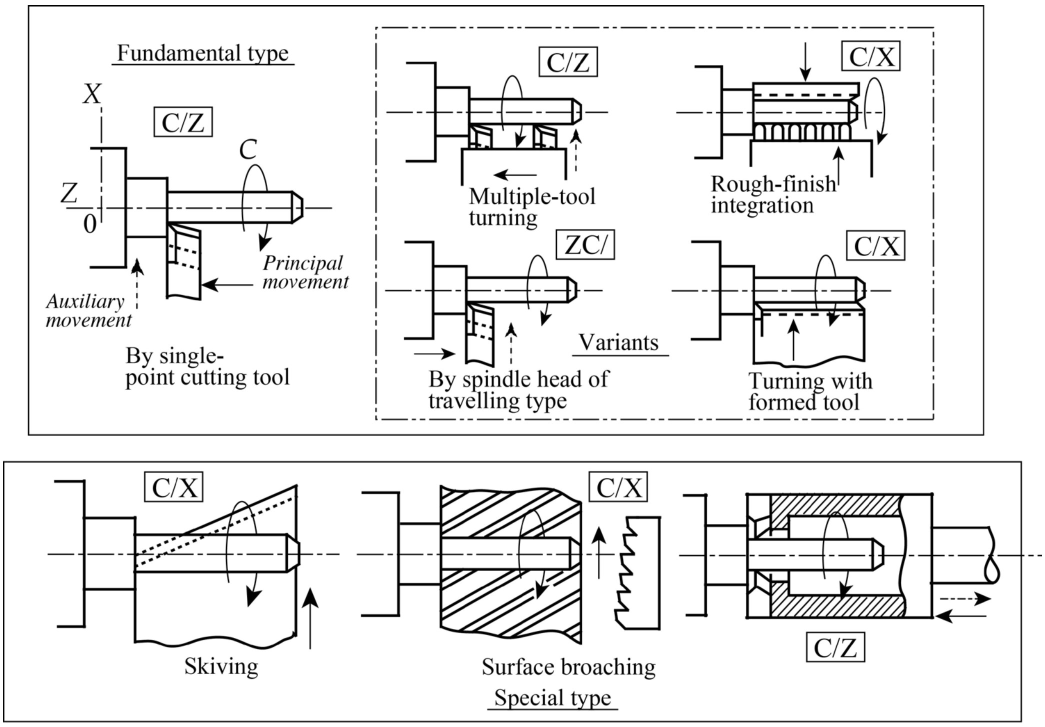
Damage of cutting tool caused by “Sand Inclusion” within casted raw material
Grooving wear of cutting tool caused by scale of forged steel
Spontaneous combustion of swarf and chatter occurance by producing saw-like swarf while machining Ti alloy
In case of Mg alloy, flammability of swarf while machining and spontaneous combusion of accumulated swarf
In cases of machining parts with higher accuracy and with thin-wall, jig and undue holding allowance should be employed
Engagement of cutting edge in work made of cartridge brass - Action of negative axial component of cutting force in turning
Use of cold-finished steel bars in part production without turn-top

Table 4.1 Some determinants for choosing preferable raw material

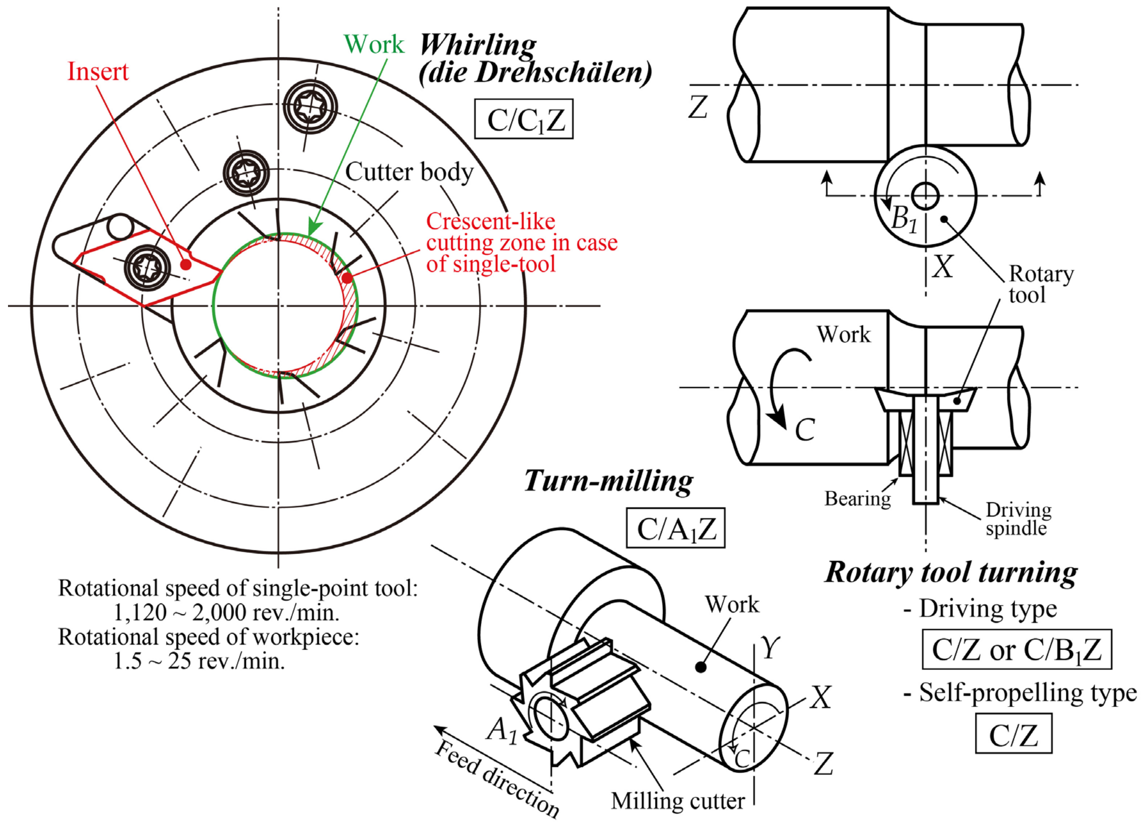
Conceptually, this issue is closely related to the problem regarding “What is the part drawing with better quality”. In this context, we must recall that the engineering designer conducts often, without any consciousness, the choice of the preferable raw material while producing the part drawing. Such an activity of the engineering designer lies in “Implicit thought pattern” and is a “Must” to produce the part drawing with the best quality. Importantly, the implicit thought pattern can be interpreted as a rough process planning beforehand. Thus, we must visualize such a thought-pattern by, for example, “Think aloud method” and describe, at least, the determinants as shown in Table 4.1. Obviously, there remain something to be seen in the visualization of the determinants, which are closely related to the experience-oriented knowledge.

Database structure

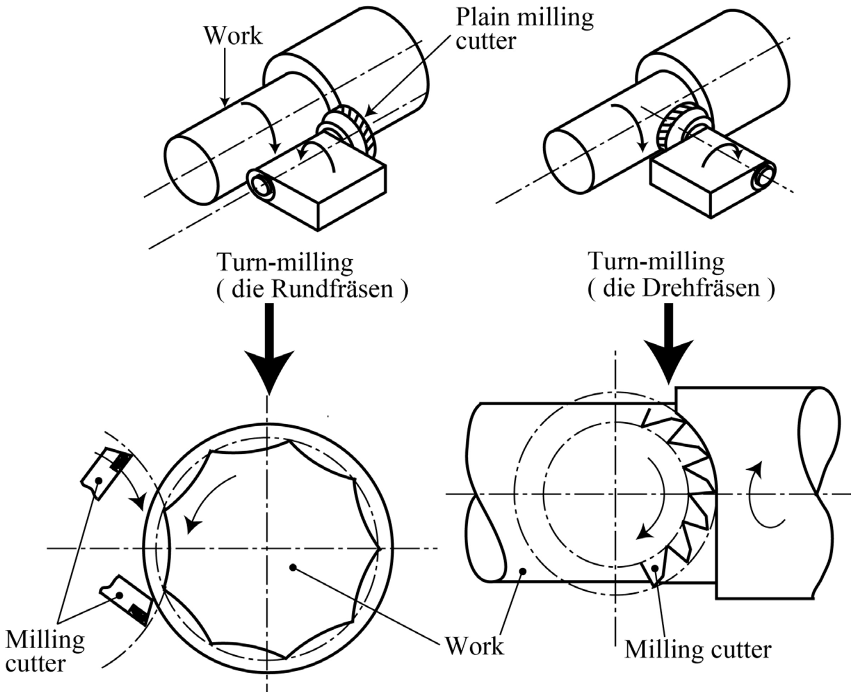
We can classify the machining methods to generate the same geometrical feature by the hierarchical system as shown, for example those for cylindrical turning (turn-top), in Figs. 4.8 (a), (b) and (c). In due course, ***a facing issue is what is a desirable database structure to fulfill the “One-to-One Relationship” mentioned above; however, at present, we have no ideas. Thus, Fig. 4.9 is a proposal based on QFD*** (Quality Function Deployment) (Höft 1999), and more specifically, the proposal can be characterized as follows.



(a) Fundamental type, its variants and special types



(b) Turn-top with rotating tool



(c) Variants in turn-milling

Fig. 4.8 Fundamental type, its variants and special types in cylindrical turning together with their functional descriptions

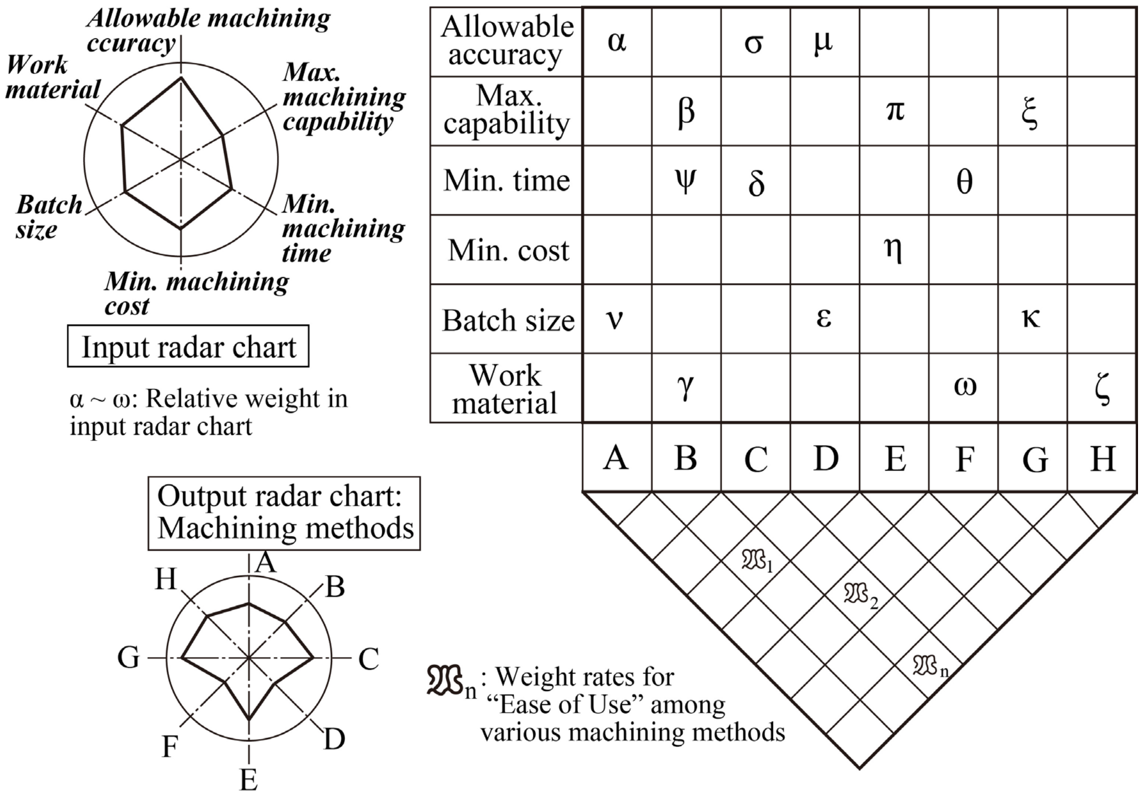


Fig. 4.9 Database concept to generate utmost desirable machining method by QFD

(1) In consideration of core attributes possible to extract from the part drawing, the characteristic features of each machining method should be evaluated.
(2) The core attributes obtained from given part drawing should be compared with those of each machining method, and some preferable methods should be chosen.
(3) By using a representative index, e.g., "Ease of Use", the utmost suitable method should be determined among some candidates.

Of course, the database mentioned above is also available for the traditional CAPP of generative type.

As can be readily seen, within the weight rates in Fig. 4.9, the further R & D subjects are as follows.

(1) Determination for characterizing functions of each machining method by six leading attributes, i.e., machining accuracy, capability, machining time and cost, and furthermore the batch size and work material. In

common senses, we believe that such characterization data were already in fruition; however, such a belief is “Myth”. In fact, we must belatedly establish the characterization data in satisfactory states. For the sake of further understanding, a forerunning achievement is shown in Fig. 4.10, which was carried out by Sorge (1984) in consideration of three representative attributes, i.e., configuration complexity and shape geometry deviation in part, and also the type of swarf.

(2) Definition of “Ease of Use” and its evaluation, which can quantify obviously the differing features among various machining methods to generate the same geometrical feature.

(3) Investigation into another suitable “Index” for choosing the optimum machining method rather than “Ease of Use”.

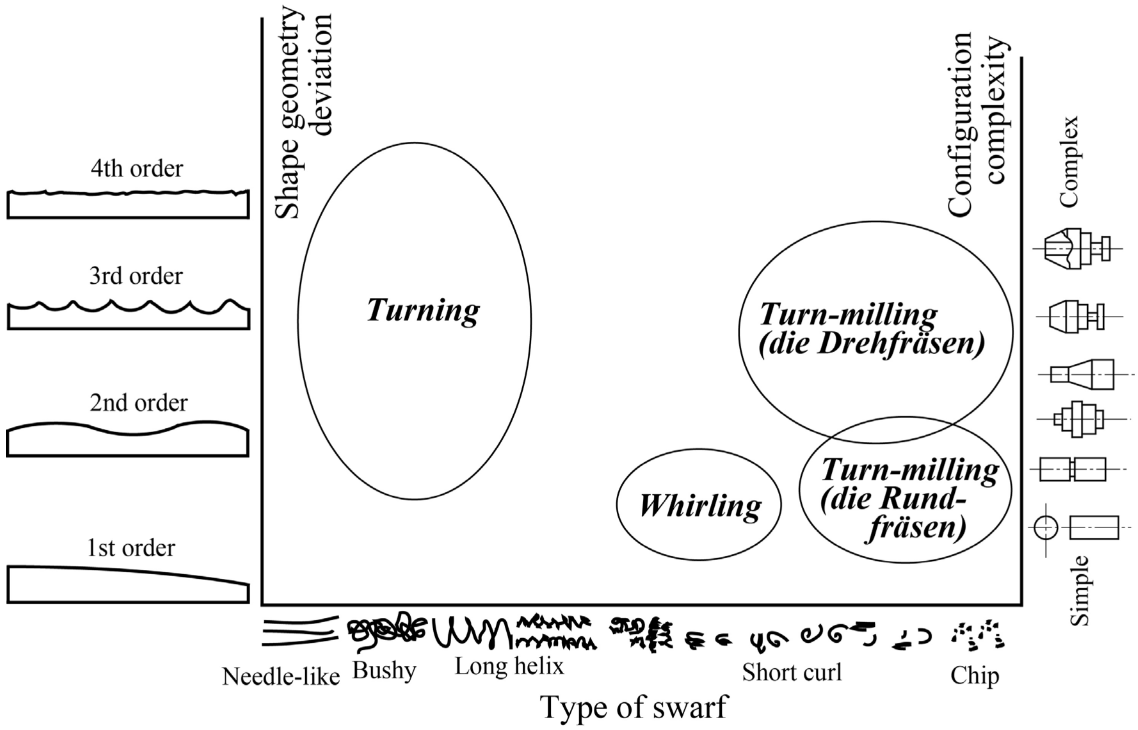


Fig. 4.10 Comparison for available ranges of turning in general, whirling and turn-milling in consideration of three attributes (by Sorge, 1984)

Admitting that QFD may facilitate to give a sure-handed relationship between the geometrical feature to the preferable machining method, we need furthermore a diagram indicating possible linkages among the machining method, types of cutting tools, turret head types and machine kinds such as shown in Fig. 4.11.

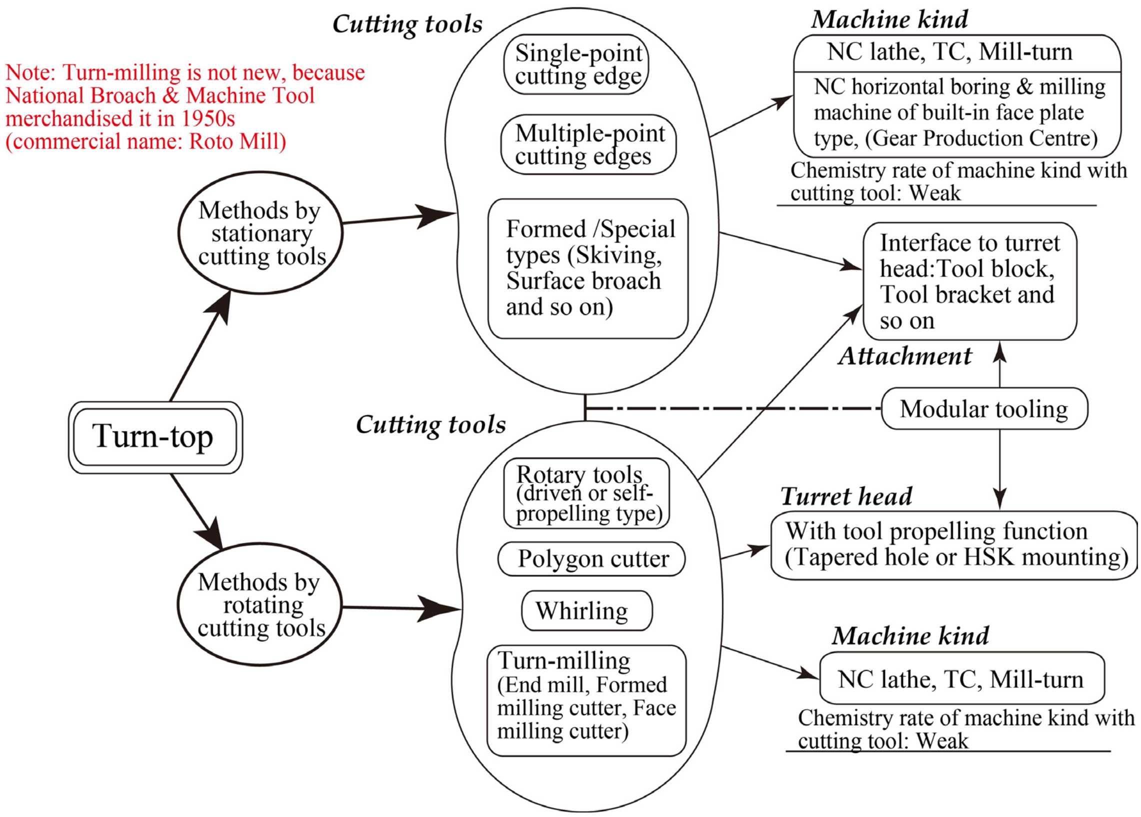


Fig. 4.11 Linkage diagram ranging from machining method to structural configuration entities - Turn-top

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Chapter 5 Concluding Remarks

In short, process planning at present has been considered in mature states, although its quality depends upon the competency of the experienced engineer to a great extent. With the advance of individual technology, which consists of the machining space, i.e., machine-attachment-tool-work system, however, process planning so far used is duly forced to change or should change itself as can be readily seen from the main body of this book.

Nevertheless, it is, in general, difficult to find the forerunning and challenging research into an innovative CAPP, which is compatible with the machining environments in the year 2020 and beyond. In fact, the smart factory is at crucial issue, and duly a new CAPP should be investigated; however, there have been, for example, no interesting applications to the "Open Project Research being conducted by MTEF" over a couple of years. This is very incredible, and thus the author would like to encourage the young researcher in conducting the research into an innovative CAPP by referring to this book.

Of special notes, we face now to contrive process planning compatible with new machining environments, and to do so, we must overcome two serious hindrances. One is, as already mentioned in detail, to establish the "One-to-One Relationship between Geometrical and Manufacturing-related Information", and the other is to establish a methodology for process planning, where we must, at least, consider the linkage diagram shown already in Fig.4.11.

Importantly, we have not had any methodologies for process planning, because of its complexity resulting from the numerous numbers of attributes being concerned, and also the necessity of incorporating grass root-like factory floor knowledge. For example, Fig. R.1 shows a typical grass root-like knowledge about machining and assembly technologies at the joint face of headstock with top cover, when guaranteeing the oil tight with economization. In fact, we used to apply the joint face without overhang, although it is very costly. In contrast, we can benefit economically by employing the top cover with overhang, which can play desirable oil tight,

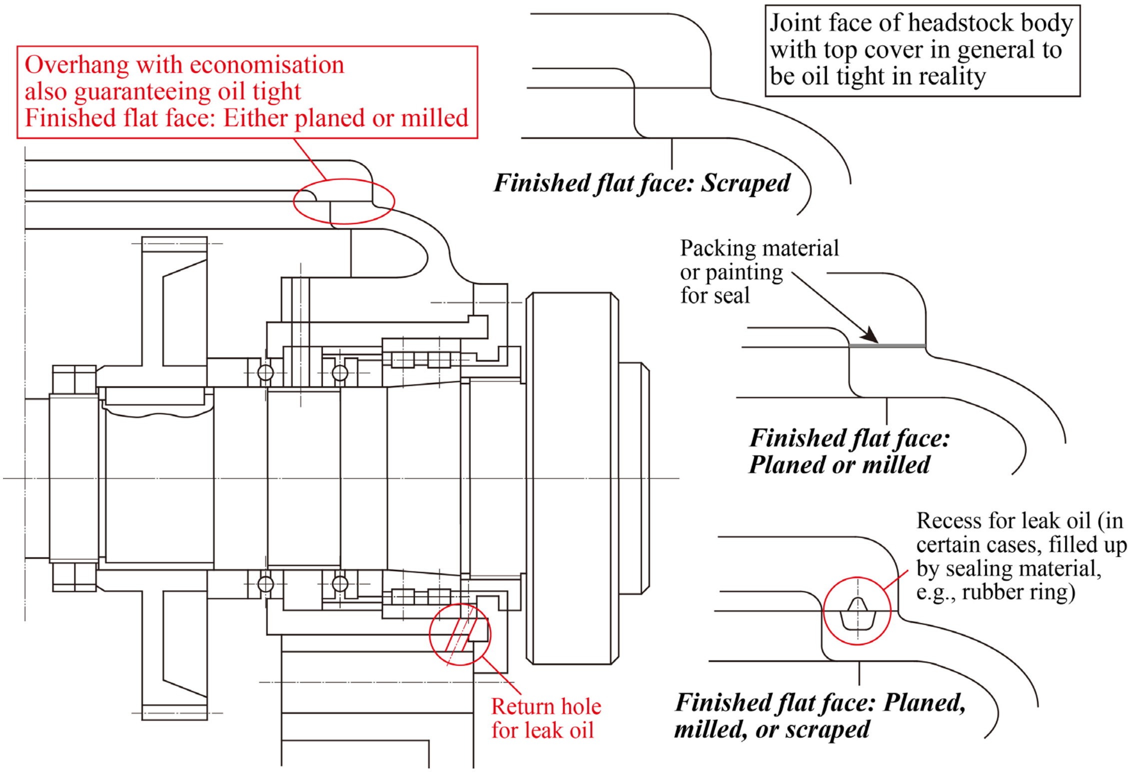


Fig. R.1 A remedy for reduction of machining and assembly cost
- In case of oil tight between headstock body and top cover

even though the joint face is rough-machined. In addition, another issue is how to transfer the manufacturing-related knowledge of the engineering designer while producing the part drawing into the methodology. For example, Table R.1 shows such knowledge in general.

In principle, we can understand the importance of these mentioned above; however, there are no ideas at present regarding what is desirable methodology in practice, and in due course, we face considerable difficulties in conducting the academic research itself.

To this end, it emphasizes that another CAPP should be established for resurrecting the recycled part and unit, which will be supplied to the assembly process in manufacturing in consideration of re-manufacturing shown together within Fig. 1.1. For example, we need to develop process planning for disintegration of recycled unit with reminding that the disintegration of the unit differs from its assembly to a large extent, e.g., loosening tightening bolt with rust, dust and sand-like particles. In case of machining, the recycled piston should be first milled to take off pitching caused by the operation, then overlaid by the Cr- or Ni-based alloy, and finally finish-machining.

Assemblability of product including compatibility of standard and purchased parts
Ease of adjustment for function and also of transportation of product
Applicable form-generating movements by machine-attachment-tool-work system
Allowable machining capability and accuracy of in-house installed machine tools - In certain cases including those in sister companies and subsidiaries
"Difficult-to-machine" properties in work material and machining restriction caused by heat treatment
Machining methods capable of achieving required accuracy and surface quality
Preparatory process analyses and planning together with cost analyses
Reduction of machining cost in consideration of batch size
Ergonomics / Ease of daily and long-term maintenance, and repair

Table R.1 Manufacturing-related knowledge being considered while producing part drawing by engineering designer

Appendix Rapid Calculation Method for Machining Cost by Using Hourly Rate

In conducting process planning, we must always pay the special attention to the machining cost, and thus, we need to have a rapid calculation method for the machining cost.

Machine operation cost (Yen/min)
Work-related cost (Yen/min)
Preparatory time (min)
Batch size

$$C = [K_m + K_z][(T_i/n) + T_e]$$

Machining cost per one part (Yen)
Purchasing cost of machine including tools (Yen)
Machining time per one part (min)

Interest rate

Where,

$$K_m = A[(1 + \alpha)/60\ T_0]$$

$$K_z = P[(1 + \beta)(z/60)]$$

Total operation time per year (hour)

Average labour cost (Yen/hour)
Rate of overheads
Required rate of worker

$(K_m + K_z)$: Hourly cost for each machining method

Fig. A.1 Simple formula for machining cost

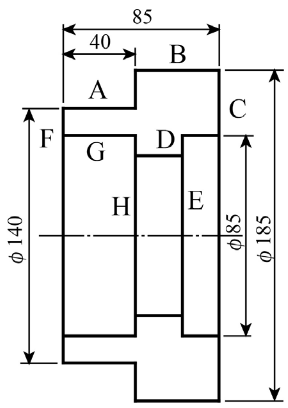
In this context, we used to a simple method based on the “Hourly Cost” as shown in Fig. A.1. Obviously, each machining method has its own hourly cost, and the total machining cost for a corresponding work can be obtained by summing up those for each machining method after carrying out the calculation procedures shown in Fig. A.2. In consequence, the hourly cost can be determined in various ways depending upon the organizational circumstances of each enterprise. For example, K_m can be determined in consideration of depreciation cost of machine tool and transportation cost of materials in certain cases.

For the sake of further understanding, a sample of the cost calculation is shown in Fig. A.3.

1. Process analyses and process planning for corresponding part drawing
2. In accordance with process planning, reconfirmation of "Machine Kind and Type", "Attachments" and "Machining Tools", and then "Estimation of Machining Conditions in General"
3. Calculation of machining time for each process based on machining condition, and then multify it by "Hourly cost"
4. Estimation of total machining cost by summing up the costs for all the processes necessary

Note: In determination of machining conditions, e.g., cutting speed, depth of cut, and feed rate, it is recommendable to refer to the values recommended by tool manufacturers

Fig. A.2 Calculation procedures for machining cost



Material：SCM 21

Bearing housing

Portion A: Rough turn-top

Depth of cut 4 mm × Feed rate 0.2 mm/rev (6 times)
Cutting speed 80 m/min, N = 160 rev/min
Feed speed 32 mm/min, Machining time around 0.8 min × 6 = 4.8 min
Hourly rate 500 Yen/min, Machining cost around 2500 Yen

Drilling

Pilot drilling：Diameter 20 mm, Cutting speed 30 m/min, Feed rate 0.5 mm/rev, N = 500 rev/min, Feed speed 250 mm/min, Machining time around 0.4 (90/250) min
Rough drilling：Diameter 60 mm, Cutting speed 30 m/min, Feed rate 0.5 mm/rev, N = 160 rev/min, Feed speed 80 mm/min, Machining time around 1.1 (90/80) min
Hourly rate 300 Yen/min, Machining cost around 450 Yen

Cutting speed V m/min = (πDN)/1,000 Feed speed f mm/min = s × N
D:Diameter mm, N:Rotational speed rev/min, s: Feed rate mm/rev

Process analyses and process planning

Material choice: Raw material - Dia. 190 × Length 90 mm — Portion A & F: Rough turning (L + LFC) 142 × 38 — Re-chucking — Drilling (D)

B & C: Rough + Finish turning (L + LFC) — D & E: Rough + Finish boring (B) + Face-end finishing (LFC) — Mandrel (jig) machining

F、G & H: Rough turning — A: Finish turning (L + LFC) — G & H: Finish boring & facing

Fig. A.3 Rapid calculation of machining cost by hourly rate

To this end, it emphasizes that the machining cost can be reduced by preferably using the grass root-like remedies such as exemplified in the following.

(1) When producing the part drawing, a "Must" is to employ the through drilling, reaming and tapping instead of those with pocket holes as possible as we can.
(2) We must use positively some major shapes and leading dimensions of cutting and grinding tools, and also attachments, which are regulated by various Standards. For example, rounding and chamfering produced by the single-point cutting tool as per the standard can reduce the machining cost together with guaranteeing the out-of-square accuracy in assembling both the parts (see Fig. 2.4).