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Theory and Practice in Machining Systems

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Preface

The machine tool engineering technology can be, in wider scope, twofold: one is the production technology consisting of the design and manufacture, and the other is the utilisation technology. Importantly, the majority of people of machine tool concerns are interested in and related to the utilisation technology; however, the matters in production technology concerns are generally at issue especially in the academia, because the machine tool underpins all the industrial sectors as represented by a famous maxim, i.e. "*Only the Real Industrial Nations Can Produce the Machine Tool and Ordnance*". In fact, we cannot produce the necessary components for all the commercial and defence supplies without having the machine tool.

In use of the machine tool, we need, in principle, the synergic knowledge ranging from the form-generating movements possible by, and also structural design and numerical control of the machine tool, through the attachment and tool, to the machining technology. It is, however, regrettable that we cannot obtain the preferable materials enabling such knowledge to be learnt at glance. In fact, all the books having been and being publicised deal with each subject mentioned above separately with narrower scope.

As a result, it appears that the machine tool and cutting/grinding technologies belong to another engineering sphere each other. For example, we can observe one of the serious problems in the self-excited chatter vibration of regenerative type. In short, to suppress the chatter vibration, we must consider the corresponding problem related to the machine-attachment-tool-work system. It is, however, worth suggesting that nearly all academic, engineering and technical reports on the chatter vibration do not state anything about the chuck and tool holder, although they play very important roles in the suppression of the chatter vibration.

In this context, we have experienced a similar story in the thermal deformation, and importantly, we must be aware of the necessity of establishing such a new viewpoint even in the machining technology with the advance of the tool and attachment. In short, we can find a considerable number of novel cutting tools, which may innovate more process planning than ever before; however, for their effective uses, we need to establish also the innovative attachment to hold them. For example, it has been the common sense to hand-lap the sharp cutting edge (sharpness-killed cutting edge) of the end mill, so that the work surface can be finished with the better quality without chipping the cutting edge. With the advent of the innovative milling chuck, however, such a remedy becomes obsolete, and on the contrary, the sharp cutting edge itself is recently recommended.

In considering the preferable leverage among the related subjects and issues depending upon the machining requirements, we need now an informative book dealing with the machine-attachment-tool-work system from the viewpoint of the user. The book proposed herein aims thus at the holistic description for the technologies necessary to the component generation by placing the stress on the machining space. More specifically, the machining space is represented by the "*Linkage Diagramme*", one of the variant of the "*Flow of Force*", and visualised obviously the structural configuration entities and concerns surrounding the machining space together with their leading linkages among one another (see Chap. 2).

More importantly, we must be aware of the increasing need for such a book with the innovative development in each entity consisting of the machine-attachment-tool-work system as follows.

(1) Prevalence of the "*Platform Concept*" in the structural design of the machine tool.
(2) Upheaval in the development of modular attachments, especially in chuck.
(3) Prevalence of cutting tools of modular and combination types.

Of these, the most influential factor is the "*Platform Concept*", i.e. user-oriented modular design, especially in the machining method-integrated kind, e.g. "*Mill-turn*". In discussing the holistic utilisation technology mentioned above, thus, the book gives us some quick notes for the platform concept (see Chap. 7).

Obviously, it is furthermore desirable to extend the concept of the "*Linkage Diagramme*" to the raw material to be machined and NC information as follows.

(1) Enhancement of machinability of the raw material with wider scope, e.g. elimination of the scale in the hot-forged raw material and work preparation considering the directional orientation in strength caused by cold drawing.
(2) Development of the innovative machining method by facilitating the NC information, e.g. turbine blade machining by whirling and slot drill moving by helical programming like boring with planetary movement.

In the latter case, we must understand the fundamentals in removal processing of unnecessary allowance at the machining point, e.g. cutting and grinding mechanism, together with differing features in various machining methods. In Part III of this book, thus, we will discuss such issues extremely placing the stress on the advanced computational method being established.

As will be clear from the above, the book can be characterised by its challenging editorial work to give the machine tool user with core and synergic knowledge. Thus, the machine tool user benefits considerably and is able to conduct the lucrative business by reading this book. In addition, the book will provide the reader in the academia and research organisation in the enterprise with some clues to carry out the forerunning and noteworthy research into and engineering development in the machining technology.

Finally, the book consists of Parts I, II, III and Appendices, and Profs. Ito and Matsumura are in charge of Parts I, II and Appendices and also of Part III, respectively.

Yokohama, Japan — Yoshimi Ito
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December 2016

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Part I
Fundamentals

Abstract

The machining technology should be learned, discussed and innovated with wider scope, i.e. that ranging from the manufacturing system to the cutting point in the machining space. To do so, we need to conduct something definite, and thus Part I will first depict an overall view for the desirable machining space in the manufacturing system. Then, we suggest the importance of the linkage of structural configuration entities within the machining space, i.e. machine-attachment-tool-work system, in discussing the leading engineering problem in the machining technology.

In Chaps. 1 and 2, primary concerns in the machining space will be detailed, for example, by using the hierarchical classification system of machining methods, closed-loop concept in the linkage of structural configuration entities and form-generating movement together with its description. Importantly, Chap. 1 provides us furthermore the knowledge about the supply of the raw material for machining and discharge of the swarf from the machining space. In short, metal-working, phase-change processing and additive processing are for the raw material and semi-finished component production.

Headnotes

In the production activities for the commercial and defence supplies, we use the factory system, which ranges from large-sized to cell configurations, depending upon the enterprise size. More specifically, primary concern in the production activity is the production morphology, which represents the life history of the product, starting from the market survey or user's order placement and terminating at the product disposal. Conceptually, the production morphology reveals the explicit and implicit representations of materials and information flows in the product history, and can be defined as follows:

"*A time series of 'Processes (Procedures)' dealing with the 'Product Creation and Disposal', ranging from the collection of market information of and order*

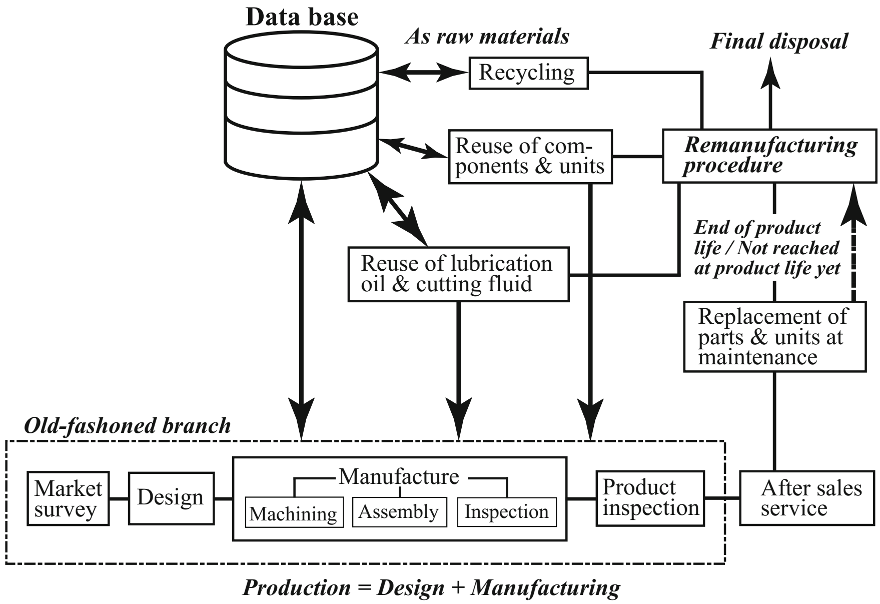

Fig. I.1 Concept of production morphology

placement by the customer, through the design and manufacturing, to the after sales service and remanufacturing".

Although depending upon the product kind and its production volume, the production morphology shows clearly the position of the machining procedure in the factory system, and thus Fig. I.1 illustrates the generalised production morphology in discrete type, and we used to specify the production morphology on the basis of the old-fashioned branch within Fig. I.1.[1] Importantly, we place now the stress on the remanufacture in Fig. I.1, in which the end-of-life product is, in general, at burning issue, in consideration of the social requirements for sustainability at present. We must, however, pay special attention to the following, because these will result in a new perspective in the production technology.

[1]In the discrete type, materials for manufacture concern, e.g. raw material, semi-finished work, finished component, cutting tool, jig and fixture, and swarf, are transferred in the pattern of "*Point-to-Point*," but not continuous flow. In contrast, in the process type, materials flow continuously, i.e. seamless material flow. The former can be observed, for example, in the motorcar, aerospace, industrial machines and machine tool industries, whereas the latter can be observed, for example, in the cigarette, petroleum refining, and cosmetic and detergent industries. In addition, we have a combination system of the discrete and process types, which can be exemplified by the large-scale integration (LSI) and sintered carbide tip manufacturing.

(1) Repair of the product in consideration of its operating history and by using the second-handed components (parts) and units, which are obtainable on the occasion of maintenance and repair.
(2) We may have some products, which are not yet reached at its life estimated at the design stage, but do not use anymore. We could obtain such products through (a) the renewal to the new product by the customer, (b) with the merchandise of new products by the competitor, and (c) by the function and performance deterioration in even new product due to the technology innovation. Of special note, we must be furthermore aware of the apparent product deterioration caused by the enactment of the new law.

Roughly saying, a group of the components can be finished and then assembled in the factory system. In general, we may finish the component by machining with various patterns, e.g. mass-production, production with medium volume and mediocre component variation, batch production and one-off production, in accordance with manufacturing requirements. In any patterns, the metal-cutting machine tool[2] can facilitate to finish the component to a larger extent. Importantly, without having the well-qualified manufacturing technology, the commercial and defence supplies required of the human society are not to be in reality, even though the product design is very outstanding. More importantly, the manufacturing technology involves much more professional subjects than our expectation, even when interpreting it with narrower scope and in relation to skills in the factory floor. In fact to understand correctly the manufacturing technology, we need to have the knowledge, at least, those ranging from the engineering material and its various processing methods, through machine tools and other industrial equipments to assembly and inspection technologies of the product.

Reportedly, the product involves two-pronged design attributes, i.e. fully quantified and ambiguous attributes, and a crucial issue in the product design is to rationally convert the ambiguous attributes into the quantified ones in consideration of the leverage between the quantified and ambiguous attributes. For example, in the motorcar, we can quantify the fuel efficiency of engine and traction force of tyre, whereas cannot quantify the roadability.

Now let us consider the machining technology from the manufacturing system point of view. In this context, we must be especially aware of the very importance of the grass root-like knowledge so far accumulated through the long-standing experience, and in part related to the culture and mindset background. Supposedly, such knowledge can be represented by the jargon in the factory floor.

With growing importance of flexible manufacturing systems (FMS) extremely in the 1980s and 1990s, we contrived various system configurations, and at present FMS of cell-integrated type are dominant across the whole industry. Obviously, the cell itself has enough flexibility, i.e. flexible manufacturing cell (FMC), and has been prevailed even in the very small-sized enterprise. As widely known, such

[2]Machine tools can be classified into "metal-cutting machine tools" and "metalworking machine tools". In this book, the machine tool represents shortly that of metal-cutting type hereafter.

system and cell have five functions, i.e. processing, transportation, storage, surveillance and maintenance, and also the software for computer-integrated manufacturing (CIM) in the lowest level (cell controller).

In flexible manufacturing, we must consider the three leading attributes, i.e. "*Flexibility*", "*Expandability*" and "*Redundancy*" in the design of system and cell, which is to be in reality by using the *modular design* (Ito 2008). In addition, when the processing function is for machining, we call it *flexible machining system* or *flexible machining cell*.

The machining function can, at present and in general, facilitate by the turning centre (TC) and machining centre (MC), and with the further contrivance of the machining function-integrated kind, e.g. "*Mill-Turn*" and MC with grinding function, compact and cubic-like flexible machining cell becomes dominant. Such a cell appears as to be a machine tool as a whole, and thus we must pay the special attention to the machining space, even when discussing the flexible machining system.

Now let us discuss the configuration changes in flexible machining system and cell for the motorcar industry for ease of understanding of time series-like variation in the machining space. In this context, primary concerns are the flexible transfer line (FTL), a variant of FMS, and its compact type, i.e. "*Transfer Center*".

Figure I.2 shows the typical FTL for cylinder block machining with 4 min. in cycle time, resulting in machining volume of 50,000 units per year. Importantly, the line is designed by the modular principle, where an MC is of basic module for machining, and the machining space within MC itself is very important from the

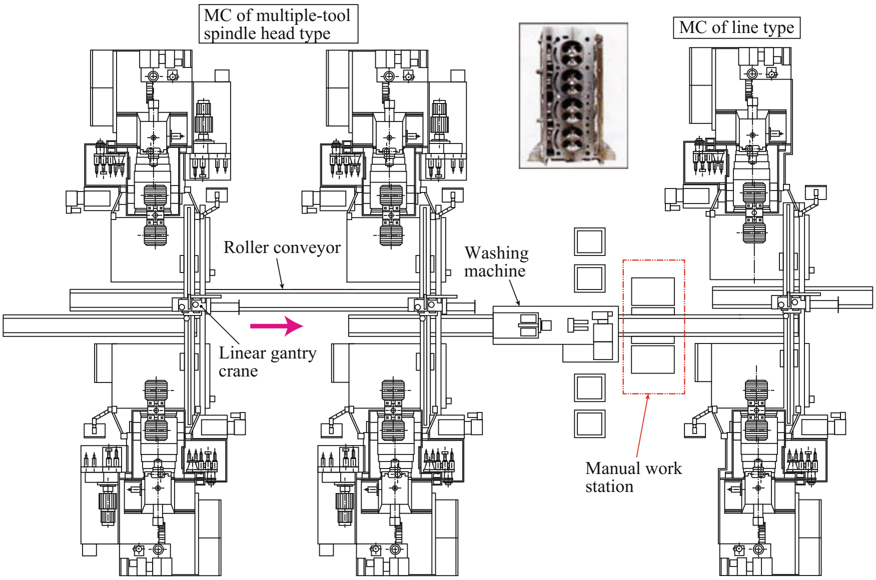

Fig. I.2 Flexible machining line for cylinder head—Fritz Werner, in 1993 viewpoint of machining technology. It is thus necessary to understand the dimensional and performance specifications of MC. For example, MC of multiple-tool spindle head type has the following specifications.

Maximum size of machining space (X, Y, Z): 1000 × 950 × 800 mm
Maximum rotational speed of main spindle: 6000 rev/min
Output power of main motor: 37 kW
Size of multiple-tool spindle head: 500 × 630 mm
Tooling system: Hollow shank system (HSK)

With the advance of the related technologies, FTL has been replaced by a group of the flexible machining cell apart from the very special machining requirements. In a certain case, the cell of stand-alone operation is employed. This aims at the further economisation of manufacturing activity, for example, by saving the installation cost and floor space for manufacturing facilities.

Figure I.3 shows a flexible machining cell complex, where a flexible machining cell is of basic module, and we can first install only a cell with the automatic pallet changer (APC). With growing volume for machining requirements, then, we can expand the cell to the cell complex by installing furthermore the new cells necessary together with the load/unload station, rail-guided vehicle and buffer, i.e. the cell having the *expandability* function. After having the two cells, we can operate the cell complex, even when one cell is down, i.e. the cell having the *redundancy* function. As will be clear from the above, we can provide this cell complex with flexibility, expandability and redundancy by using the modular design.

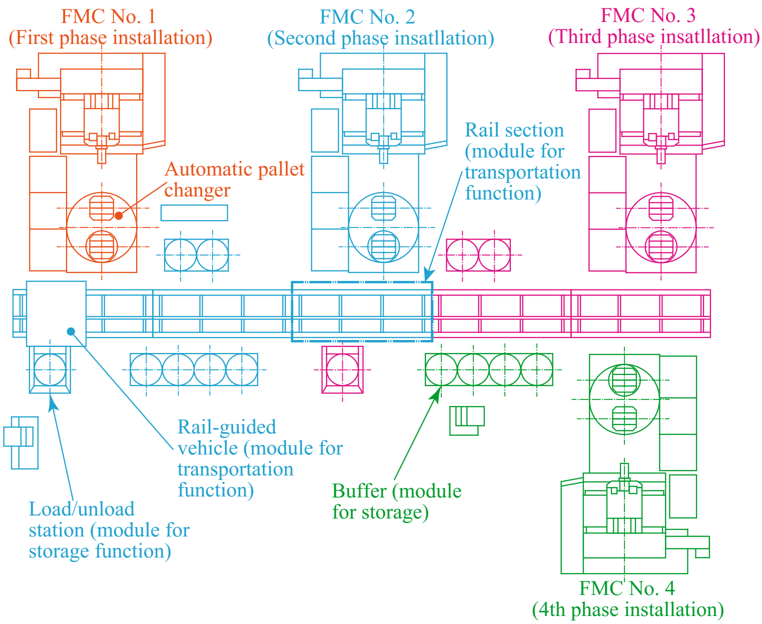

Fig. I.3 Flexible machining cell complex (by Cincinnati Milacron, 1990s)

In the middle of the 2000s, a facing issue was the compactness of the flexible machining cell, and in due course, its variants have been contrived. Of those, the "*Transfer Center*", i.e. FTL of compact type, is now in leading position. Importantly, the "*Transfer Center*" may facilitate the batch production, which is being prevailed in the motorcar industry. Typically, Fig. I.4 shows a "*Transfer Center*" of ANGER-brand, whose machining capability is compatible with those carried out by 2–5 MCs. In contrast to the head changer in the past, the work spindle can travel and rotate, and the work can be machined by single-tool spindle head, multiple-tool spindle head and various tools mounted on the turret head and tool cassette. Paraphrasing, the "*Transfer Center*" is one of the modernised head changers.

In the past, a leading variant of FTL was furthermore the dial machine, i.e. transfer line of rotary indexing type, and for example Witzig und Frank has merchandised its advanced type as shown in Fig. I.5. In this case, the machining space consists of not only the machining function, but also the transportation and storage functions, as will be clear from top and bottom-right of Fig. I.5. In contrast, the machining space of flexible machining cell consists of only the machining function.

To this end, it emphasises that we must pay certain attention to the machining space within the machining station, even when discussing the flexible machining system.

Now let us discuss furthermore the leading engineering problems in the machining space.

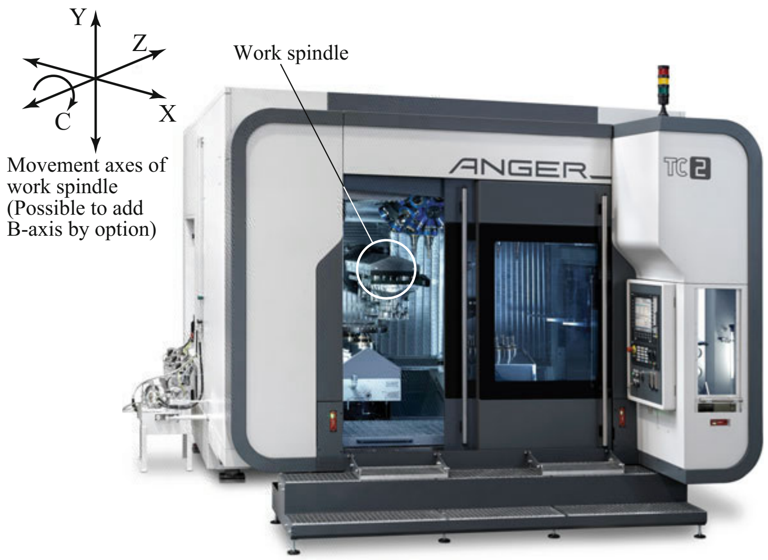

Fig. I.4 Appearance and machining space of "Transfer Center" (by courtesy of Anger 2014)

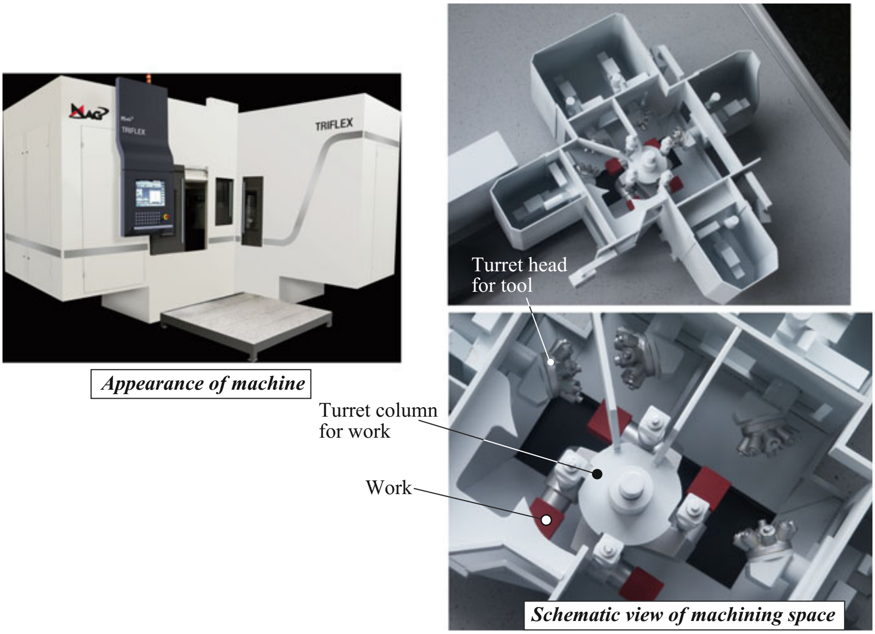

Fig. I.5 "Transfer Centre" of rotary indexing type (by courtesy of Witzig und Frank 2009)

In the functionality and performance contexts of the machine tool, there are the three leading design attributes, i.e. "*Better Machining Accuracy*", "*Machining with Higher Linear and Rotational Speeds*" and "*Heavy-duty Cutting Capability*". From the viewpoint of machining space, these result in the leading engineering subjects for the *chatter vibration* and *thermal deformation*.

Figure I.6 is the scenery of the machining space within TC, which consists of the structural body components of the machine tool, attachments, cutting tools and work. As can be readily seen, we must deal with the engineering problems mentioned above by using the systematic and synergic points of view, i.e. those in machine-attachment-tool-work system. Importantly, with the advent of the machining function-integrated kind like "*Mill-Turn*", we must solve more unimaginable and uncountable problems ever than before. Thus, we will discuss quickly the present perspectives for the chatter vibration and thermal deformation, placing the stress on the machining space-dependent aspects.

Chatter Vibration

In nearly all research papers and engineering reports, it is first stated in the headnote that the chatter vibration is one of the dynamic behaviours in the machine-attachment-tool-work system. In contrast, they do not state, for example, the detail for work and tool holding in the body text. In this context, Doi et al. (1982, 1985) investigated the self-excited chatter vibration of regenerative type in turning with the three-jaw chuck and unveiled the mingling effect of parametric vibration. More

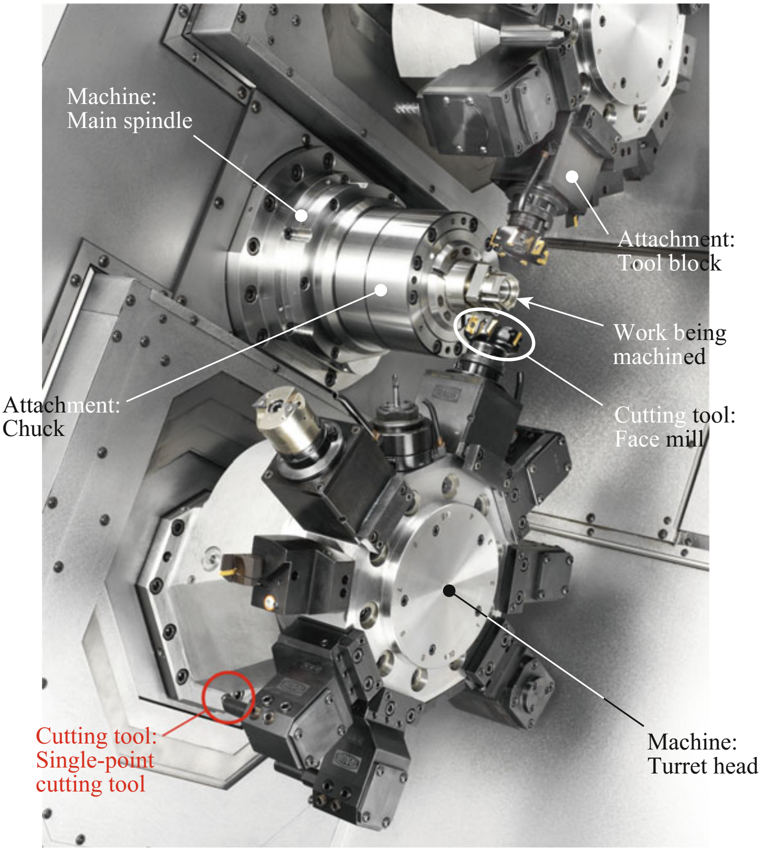

Fig. I.6 Scenery of machining space (by courtesy of Traub 2009)

specifically, the work held by the three-jaw chuck shows the directional orientation in its stiffness, which causes a parametric vibration, and deteriorates considerably the anti-chatter capability.

Another typical evidence is the lower-speed stability. The stability limit decreases theoretically in the lower-speed range of the main spindle; however, in practice, the stability limit increases considerably in the same speed range. Since 1960s, it has been believed that the lower-speed stability is caused by the interference between the flank (relief face) of the cutting tool and the wavy surface of the work, resulting in the increase of damping. Admitting the validity of such a belief in part, we must be aware that there are various damping sources in the machine-attachment-tool-work system not only at the cutting point but also other joints within the system. Of special note, we must produce the "*Damping Capacity Distribution Diagramme*" of the system, at least, at the machining space, as similar as the "*Rigidity Distribution Diagramme*" of the machine tool structure as a whole (Koenigsberger and Tlusty 1970).

Table I.1 Dimensional specifications of milling cutters (by Monnin, Dissertation of ETH Zürich)

Tool-holder assemblies	Type	Diameter mm	Free length mm	Number of teeth	Helix angle deg.	Engaging angle deg.
T1	Insert end mill	40	175	5	10	+90
T3			100			
T8	End mill (sintered carbide)	10	103	2	30	
T10	Face mill	63	90	5	20	+45
T12	End mill (sintered carbide)	16	124	4	40	+90
T15		12	171	2		
T16	Round insert end mill	40	116	5	4	—

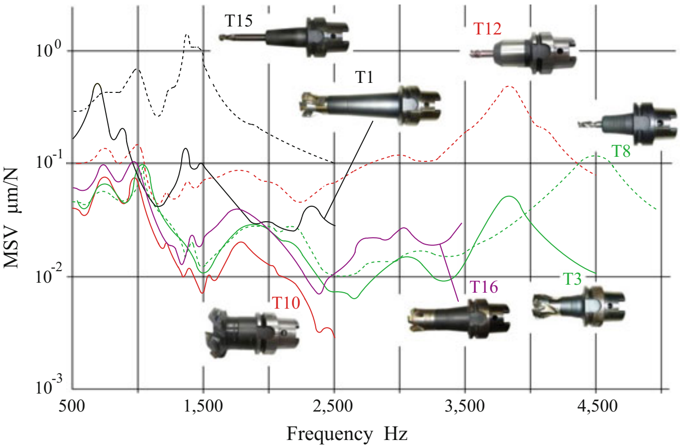

Fig. I.7 Receptance functions at tool tip for various tool-holder assemblies (by Monnin)

Importantly, Monnin (2013) has measured the frequency response in the first bending mode of the main spindle in still stand, when varying the milling cutter and its holding device, as shown in Table I.1 and Fig. I.7. The experiment was carried out by using the quinaxial-controlled MC of Mikron Agie Charmilles brand (Type HPM) and by milling the work made of either carbon steel (Ck 45) or Al-alloy (EN AW-6082 T6). In addition, the frequency response was measured by impulse excitation and also by detecting the corresponding signal with the accelerometer. In Fig. I.7, furthermore the maximum singular values (MSVs) are an index to represent the maximum amplitude of receptance function. As can be readily seen, we can observe the remarkable differing feature when varying the milling cutter and its holding device.

With the growing importance of the higher-speed machining in the aircraft industry, we face a new problem regarding the availability of the stability chart,

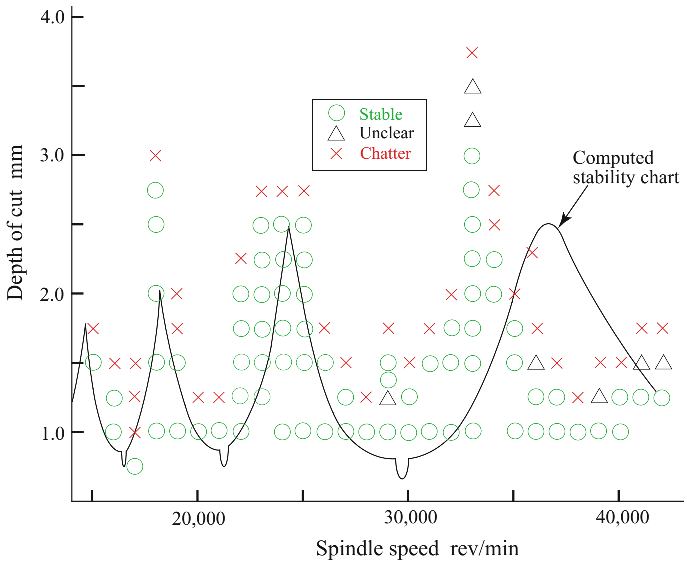

Fig. I.8 Comparison between computed stability chart and experimental values (by van Dijk et al.)

when investigating the preferable cutting condition without the chatter vibration. In this context, Van Dijk et al. (2008) reported the discrepancy between the stability charts obtained theoretically and experimentally as shown in Fig. I.8. It is very interesting that the computed stability chart differs considerably from the experimental one at the higher-speed range of main spindle, i.e. up to 27,000 rev/min. They suggested that such a discrepancy is caused by the speed-dependence behaviour of the spindle dynamics.

More specifically, the theoretical stability chart was computed for the milling machine of Mikron brand (Type HSM700) with the two-flute end mill (10 mm in diameter, 57 mm in length), which was held by shrink-fitting. Of note, the necessary data for computing the stability chart were obtained by the impulse hammer method, and also the cutting test was carried out for Al-alloy 7075 with slot (full circular) milling.

Importantly, Schmitz et al. (2004) publicised, earlier than that of Van Dijk et al., a similar result, i.e. considerable difference between the theoretical stability chart and the experimental data in the higher-spindle speed while end milling. Apparently, we can observe such an interesting behaviour when the rotating speed is more than 17,000 rev/min. In addition, a machine tool manufacturer has an experience, in which the blur-like or micro-beat-like chatter marks can be clearly observed while wet-machining the Al-alloy with 3-flute end mill, i.e. side cutting pattern of full length, and more than 11,000 rev/min in cutting speed.

To this end, thus, it emphasises that the chatter vibration problem should be investigated in consideration of the state of machining space as well as the cutting point.

Fig. I.9 Total enclosure for TC—Type SPRINT 50 linear (by courtesy of Gildemeister 2009)

Thermal Deformation

With prevailing the conventional TC and MC, the total enclosure becomes popular to enhance the marketability from the industrial design point of view. As can be readily seen from Fig. I.9, the total enclosure affects the thermal behaviour of the machine tool as a whole from both the heat dissipation and the accumulation to some extent.

Jędrzejewski et al. (2007) conducted an interesting research into the influence of the enclosure in the lathe for higher-speed machining. Although they did not show the detail of the model having been used in the research, they proposed first a mathematical model for the thermal deformation together with considering the environment temperature surrounding the machine. Then, they identified the thermal deformation of the main spindle by measuring it with the straight edge made of quartz.

Importantly, they suggested extremely that the temperature of the structural body component changes with certain time delay due to the variation in the ambient temperature, and then they eyed the heat accumulation due to the guard placement. Fig. I.10 reproduces some typical influences of the cover to the displacement in main spindle, where the Z-axis is identical with the spindle axis. As can be readily seen from the measurement, the semi- and total enclosures have considerable and certain influences on the displacements in the directions of Y and Z axes.

In general, we can observe various heat sources in the machining space, and the heat generated is dissipated in part to the environment through the enclosure. In contrast, the temperature distribution in the machining space is influenced by the change in the environment temperature.

Of special note, we must thus understand the mutual effects in the 3-dimensional heat flows between the machining space and the surroundings. Accordingly, it is necessary and inevitable to identify each heat source and its influencing region, and thus a concept of “*Thermal Volumetric-Space*” is proposed herein as shown in Fig. I.11. This concept is to visualise a cell-like room, in which the temperature

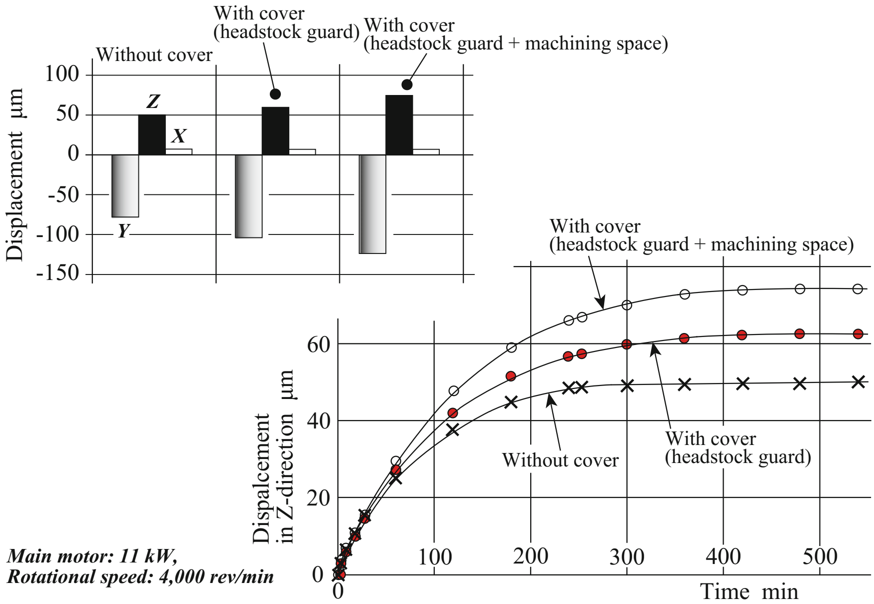

Fig. I.10 Influence of enclosure on thermal deformation in main spindle of lathe (by courtesy of Jędrzejewski et al.)

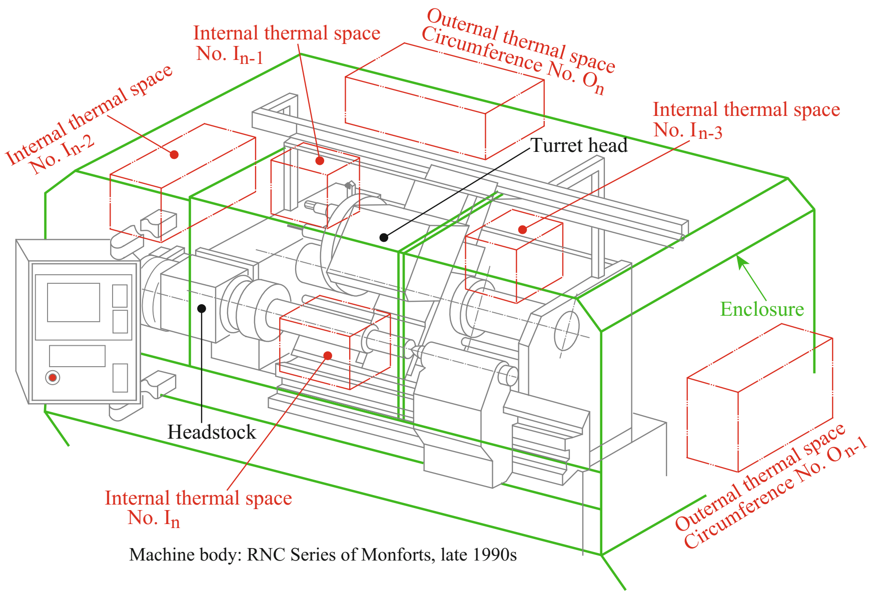

Fig. I.11 Concept of "Thermal Volumetric-Space"

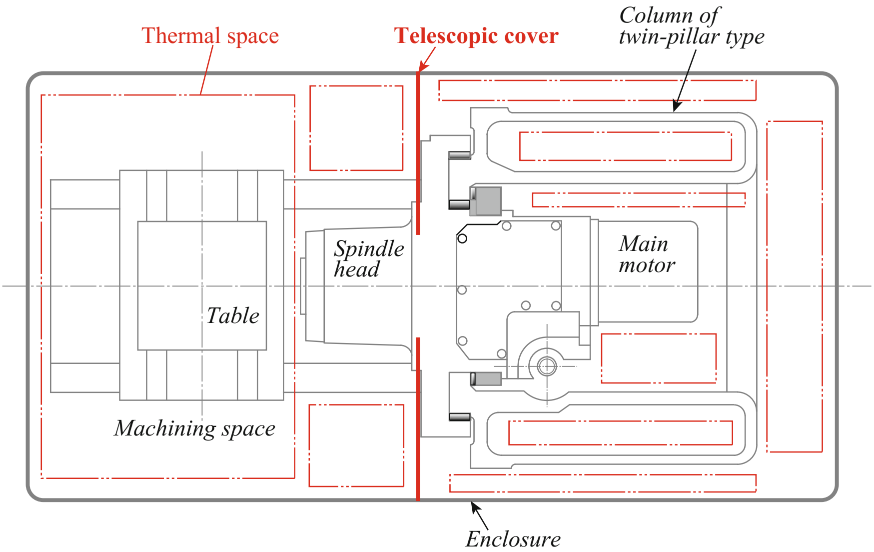

Fig. I.12 Allocation example of “Thermal Space” within enclosure

distribution is nearly constant, and in general the machine body may be partitioned into several rooms by the structural body components and configuration entities. Obviously, we can detail the heat flow among volumetric spaces by using their distribution diagram. Conceptually, the “*Thermal Volumetric-space*” may be simplified into the two-dimensional thermal space as shown in Fig. I.12, provided that the machining and factory spaces are in the constant temperature distribution in the vertical plane, and we may benefit from it to some extent.

In the thermal deformation, it is furthermore important to determine correctly the dynamic and thermal boundary conditions, and to do so we must consider the “*Dynamic and Thermal Closed Loop*”. In fact, the thermal state of the machining space reaches at stable after repeating several times the closed-loop effect between the dynamic and thermal changes. For example, Fig. I.13 reproduces the temperature rise of the model spindle supported by the tapered roller bearing with high-speed adapter (Lee 1991). As well known, the high-speed adapter was contrived by Timken. More specifically, the thermal deformation of the outer ring is quicker in radial direction than that in axial direction, and thus small clearance at the land B can be facilitate the release of the dynamic constraint of the outer ring, resulting in the reduction of heat generation.

As can be readily seen, the high-speed adapter can reduce the temperature as expected, whereas we can observe the spike-like temperature rise by placing the adapter as shown also in Fig. I.13. This implies that the high-speed adapter shows a stick-slip like movement in both the radial and axial directions, and induces the complexity in the closed-loop effect. Importantly, the more increase the rotational speed of spindle and loading, the much more apparent is the closed-loop effect

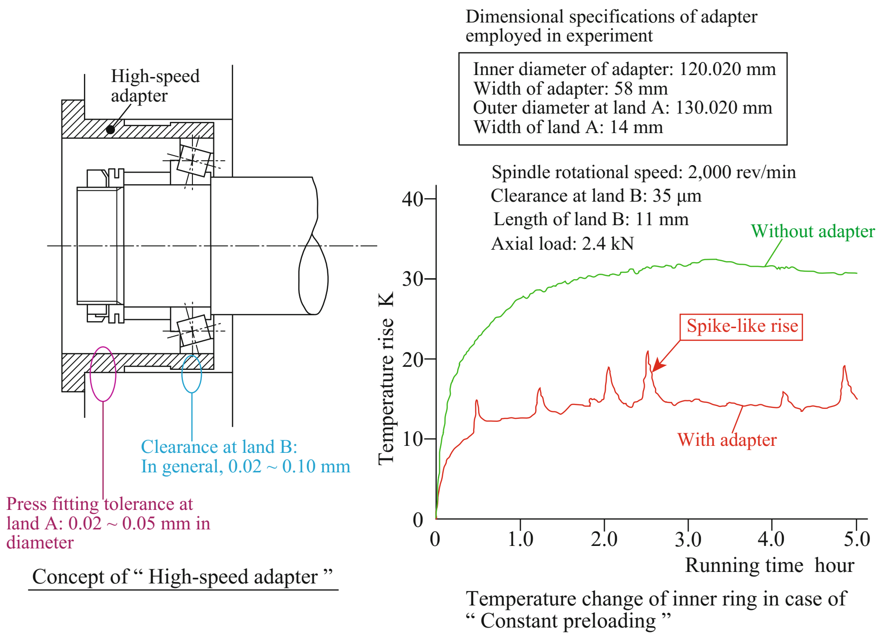

Fig. I.13 Temperature rise in spindle with and without high-speed adapter—implication of "closed-loop effects"

In many respects, it is thus necessary to integrate the "*Thermal Volumetric-space*" and "*Dynamic and Thermal Closed Loop*" as shown in Fig. I.14. Eventually, we will be able to scrutinise the thermal behaviour in the machining space, extremely discussing the mutual effect between the machining space and the environmental field through the enclosure. Importantly, it is furthermore possible to consider the "*Dynamic and Thermal Closed Loop*" within each "*Thermal Volumetric-space*", and we can expect the authentic prediction of the machining accuracy.

Within the thermal behaviour context, we must consider another leading issue, i.e. uncertainty in the determination of the thermal boundary condition. Such an uncertainty is, in general, caused by the flows of air and cooling media within the machining space and structural body component, around the machine body as a whole and within the enclosure, and furthermore around the outer surface of enclosure and factory floor.

In fact, we cannot determine the heat dissipation capability from the surface of machine body and heat transfer pattern in the machining space without considering such an uncertainty.

Figure I.15 reproduces such flows of air in the rotating jaw chuck and grinding wheel (see Sect. 5.4, Ito 2010). In both the cases, we can visualise the flow pattern by using both the smoke wire method and the *Taft Method*, and observe the very complicated flow pattern caused by the protruded jaw from the chuck body and the

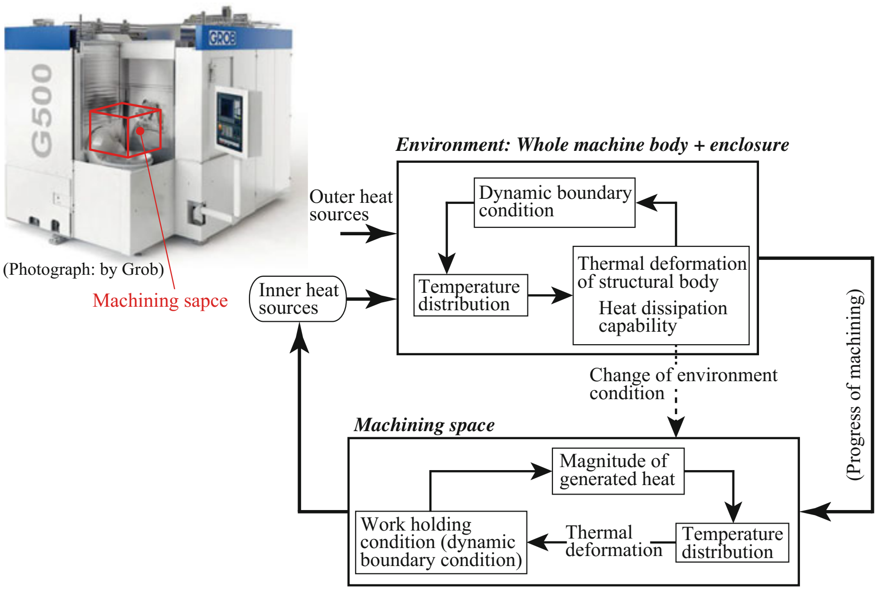

Fig. I.14 Closed-loop effect of dynamic and thermal behaviour within machining space and environment

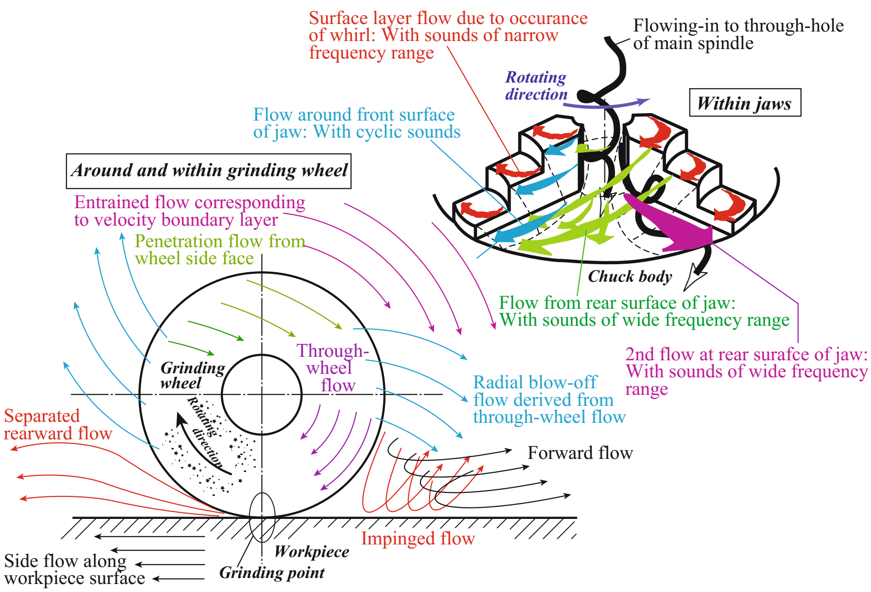

Fig. I.15 Very complicated flows of air for rotating chuck and grinding wheel porosity of the grinding wheel. Obviously, these flow patterns may affect the thermal boundary condition of the machining space. Importantly, the flow pattern in chuck is closely related to the jaw configuration and can be characterised as follows:

(1) Flow-in to through-hole of main spindle: Depending upon resonance characteristic of air column
(2) Surface layer flow: Depending upon jaw configuration
(3) Flow around front surface of jaw: Depending upon jaw height along radial direction and jaw rotating speed
(4) Flow from rear surface of jaw: Depending upon chuck body configuration
(5) Second flow at rear surface of jaw: Depending upon cross-sectional shape of jaw along radial direction

Of course, the flow pattern of grinding wheel is related to the abrasive grain size, kind of binder and rate of porosity, and more importantly, the flow pattern can facilitate the magnitude of the local heat transfer coefficient as will be discussed below.

In the flow pattern in the grinding wheel, primary concern is the entrained flow, the layer thickness of which is equal to the radius of the grinding wheel or much more than the radius.

It is very interesting that the flow of air is in nonlinear relation to the lower rotational speed and becomes linear at the higher rotational speed, respectively. Supposedly, various flows seem to be relevant at the lower-speed range, where the porosity of the grinding wheel is very effective. As can be readily seen from the flow behaviour of Al-alloy disc, with the increase in the rotational speed, the laminar flow becomes dominant even in the grinding wheel.

In addition to the flow pattern, Saito et al. (1983) reported some measured results for the local heat transfer coefficient on the work while surface grinding as shown in Fig. I.16. Obviously, we can observe some interesting behaviour as follows:

(1) In comparison with the case of Al-alloy solid disk, the porosity of the grinding wheel has large effects on the local heat transfer coefficient. Importantly, the more porosity a grinding wheel is, the more increase and wider range are the heat transfer coefficient and its distribution, respectively.
(2) The larger heat transfer coefficient appears at the area, where the impinged flow is dominant.

It emphasises again that the thermal boundary condition should be determined in full consideration of the flow of air within the machining space. Of special note, we must be also aware of the importance of the measuring method for the three-dimensional distributions of both the temperature distribution and the thermal deformation within the machining space.

Summarising, the thermal deformation should be estimated in consideration of (1) the mutual interference among various heat sources within and around the machine tool as a whole including the factory floor environment, (2) closed-loop

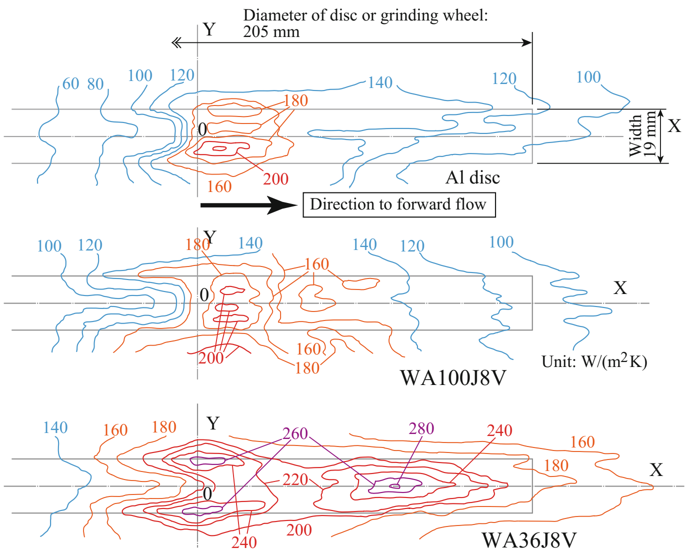

Fig. I.16 Effects of abrasive grain size on local heat transfer coefficient and its distribution in grinding wheel

effects, (3) flows of air within the machining space, enclosure and factory floor and also (4) coolant within the machining space.

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Chapter 1
Metal Processing Technology in General—Importance of Hierarchical Classification

Prior to discuss the machining technology, we must understand the *bird's-eye view* of the metal processing technology, which may handle other non-metallic materials, e.g., plastics, glass and ceramics, in certain cases. Of note, the metal processing technology can be, in general, classified into the (1) machining (metal removal processing, swarf-generating type), (2) metalworking (metal non-removal processing), (3) phase-change processing, e.g., welding, casting and plastic injection moulding, and (4) additive processing (rapid prototyping) technologies. In addition, we must use the surface treatment technology, such as coating, sand blasting, shot peening and so on.

More specifically, the material as a whole or in part is first melted into the liquid state, and then solidified again in the phase-change processing. It is also notable that the additive processing has been rapidly improved its technological standard. For example, the Airbus Defence and Space has tried to produce the rocket component by using 3D printer of laser processing type, i.e., one of additive processing methods, which is made of platinum-rhodium alloy (Pultarova 2015).

Importantly, the metal removal processing is, as literally shown, to remove the unnecessary allowance, i.e., undue proportion, from either the raw material or semi-finished component as the swarf, whereas the metalworking can deform all the raw material into the finished or semi-finished components without generating the swarf. More importantly, the availabilities of these processing technologies depend upon the properties of product, and thus the production engineer should learn first their overall views together with their advantages and disadvantages from both the technological and economic aspects. Obviously, the machine tool manufacturer and user must learn extremely metal removal processing, especially the machining technology in details.

To ease the following discussion, several turning methods for generating the outer surface of the cylindrical component are shown in Fig. 1.1a–c. At a glance, we have certain difficulties in understanding the differing features of each method. Eventually, we face a problem for choosing the preferable method, when providing

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