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[Contribution]

Trends in Recent Machine Tool Technologies

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Recent trends in the machine tool technologies are surveyed from the view points of high speed and high performance machine tools, combined multi-functional machine tools, ultraprecision machine tools and advanced and intelligent control technologies. The machine tools are bases of manufacturing industries and they are strategically important products for Japan. The views of the author towards the technical developments in both hardware and software are introduced together with the world wide trends in the relevant fields.

1. Introduction

At present, the machine tool industry worldwide is enjoying unprecedented demand, and the industry's output is apparently even failing to satisfy current demand. Japan's machine tool industry, in particular, has boasted the greatest share in the world since 1982, and its share has been exceptionally high in the last two years. In order for Japan's machine tool industry to maintain this share, I believe that the enterprises involved in it must remain committed not only to expansion and advancement of their product facilities, but also to steady research and development efforts. They must continue to add more value to their products in order to cope with future needs and maintain competitiveness compared to machine tool manufacturers in other nations.

In this paper, I intend to report on current topics about recent machine tools and trends in the research and development commitments of the Japanese machine tool industry, highlighting the efforts of The International Academy for Production Engineering (CIRP), an organization of which I am a member.

2. High-Speed, High-Efficiency Machine Tools

It is well known that demands are mounting for greater maximum main spindle speeds and feed speeds—in other words, that machine tools of higher speed and higher efficiency are much needed. [1] Background information about high-speed machine tools and supporting technologies, and their resultant advantages are summarized in **Table 1**.

In this section, I will focus on the avoidance of chatter vibration, which is one outstanding advantage of high-speed, high-efficiency machine tools, as other engineering topics are discussed in papers by other researchers.

In the period of the 1960's and 1970's, there were research efforts worldwide on the chatter vibration of machine tools. As a result, the underlying principles behind so-called regenerative chatter vibration and forced chatter vibration were clarified, and basic solutions were proposed.

Unfortunately, however, examples of further systematic research efforts have been rare.

In recent years, avoidance of chatter vibration has been posing a new challenge in the machining of

Table 1 Background, supporting technologies and advantages of high-speed, high-efficient machine tools

High-speed, high-efficiency machine tools
(Background, supporting technologies)
● Need for highly efficient machining and decreased costs
● Development of high-speed main spindles and high-speed feed means (linear motors, etc.)
● Advances including the development of high-speed machining capable tools and progress in machining techniques
(Advantages)
● Decreased processing times (improved efficiency)
● Improved machining accuracy and better quality of finished surfaces
● Prevention of chatter vibration

hard-to-cut materials as well as in high-speed, high-efficiency machining of aluminum materials for aviation purposes. Generally, chatter vibration is avoided by reducing the depths of cuts and cutting speeds (low-speed stability), but it is possible to avoid chatter vibration by increasing spindle speed. This fact was already known from research done in the 1960's. Since high-speed spindles boasting this ability were not available in those days, however, this fact was regarded simply as a theoretical possibility. In the mathematical field, it was also difficult theoretically to handle chatter vibration in milling processes, including end milling. Notwithstanding, Prof. Y. Altintas et. al. obtained results for stability graphs such as the one shown in **Fig. 1**. This graph shows that chatter vibration does not occur in the region of depths cut below the stability lobes relative to spindle speeds on the horizontal axis. Though detailed discussion of this finding [2)] is omitted in this paper, the underlying principle of chatter vibration can be understood from the expressions and diagrams given to the right of this graph. Variations in chip thickness are caused by differences between the roughness of the finished surface generated by the immediately previous revolution of the main spindle or by an immediately previous cutting edge and the roughness of the finished surface currently generated by the current cutting edge. This variation in chip thickness contributes to variation in the cutting force and contributes to continuing vibration. If we can run the main spindle at a higher speed that is equivalent to the vibration frequency, then the difference between the phase of vibration resulting from the immediately previous revolution and the phase of vibration deriving from the current revolution can be effectively controlled, thereby eliminating variations caused by chip thickness. If such a condition is realized, chatter vibration will not occur even with greater cut depths.

Utilizing this principle, high-speed, high-efficiency cutting has been implemented for aircraft components made of aluminum and other materials. Given this, there has been mounting interest in the dynamic characteristics of a main spindle system that includes a main spindle, chuck and tools. As a result, the interrelation of bearings and other design factors with the dynamic characteristics of the main spindle and main spindle system has been clarified both theoretically and experimentally, and this achievement has been applied to the design of main spindles. Recently, various software packages are also being used frequently for analysis and design. The theoretical study of main spindle designs will become increasingly important.

3. Combined Multifunctional Machine Tools

In addition to high-speed, high-efficiency, cutting-capable machine tools, research on machine tools is currently focused on combined multifunctional machine tools, including 5-axis machining centers and combined multifunctional turning centers. The background and advantages of combined multifunctional machine tools are summarized in **Table 2**. Combined multifunctional machine tools can be roughly categorized into turning centers (TC) that have been developed from lathes and machining centers (MC) that started as milling machines.

A portion of the investigations into machining applications with combined machine tools based on lathes is illustrated in **Fig. 2.** In addition to machining of bores, outer circumferences and end faces, certain applications are executed for slope machining and

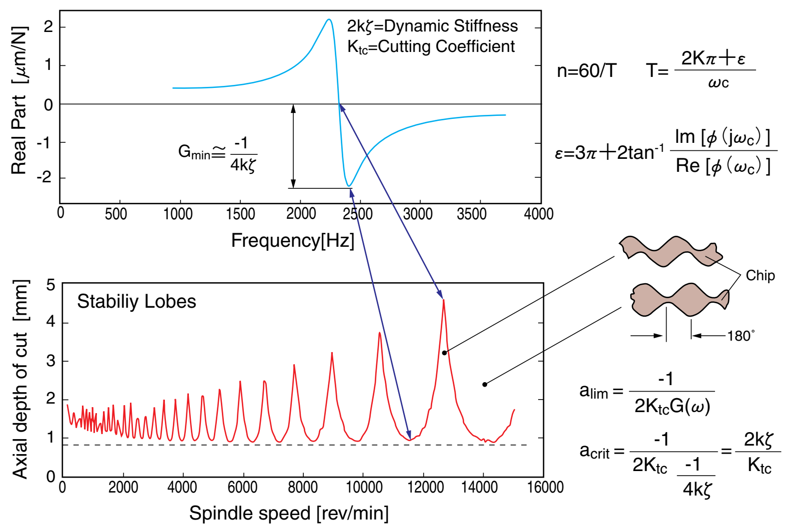

Fig. 1 Stability chart of regenerative chatter vibration (Y. Altintas)

hobbing. Recently, a main spindle mounted to an area equivalent to a turret is capable of not only auxiliary cutting processes, such as end milling, but also to more demanding milling processes. In addition, lathe-based machine tools that resemble milling machines have been developed. One example of such a combined machine tool is shown in **Fig. 3** (Mori Seiki Co. NT5400DCG).

Table 2 Background, supporting technologies and advantages of combined multi-functional machine tools

Simultaneous 5-axis control machining center (e.g.: three orthogonal axes and two rotational axes) **Combined machining turning center (e.g.: lathe and 2nd main spindle, B axis, Y axis, etc.)**
(Background, supporting technologies)
• Need for high-precision, high-efficiency machining to make more advanced (complicated) parts and components
• Increased sophistication of supporting software (CAM)
• Development of high-precision, high-efficiency machine elements (e.g.: DD-motor driven tables, etc.)
(Advantages)
• Improved machining accuracy, reduction in machining time (one-chuck process)
• Machining of complicated shapes

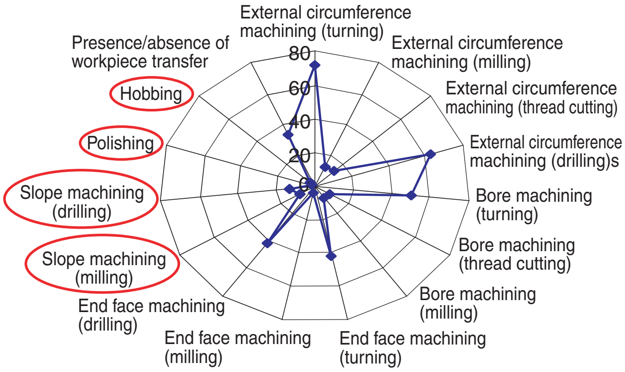

Fig. 2 Survey of machining examples by combined multi-axis machine tools based on turning machines

Many different 5-axis machining centers have been developed. In particular, in addition to orthogonal 3-axis vertical and horizontal machining centers, many simultaneous 5-axis control machining center products that have work tables with two additional axes for rotation and oscillation are used widely. Most recently, some machining centers have a work table driven by a DD motor and a high-speed, high-power rotary table capable of high-speed indexing, and they feature the functions of vertical turning centers. As mentioned above, deriving from either lathes or milling machines, combined multifunctional machining tools may evolve into novel machine tools that incorporate features of both turning centers and milling machines.

Combined multifunctional machine tools have advantages that include the following. They are capable of machining complex forms that require simultaneous control of five axes. Loss in machining accuracy from dismounting and remounting the workpiece is prevented because once a workpiece has been mounted to the chuck, all machining processes are executed without need for rechucking the workpiece. As the needs for function-intensive parts and components increase, advanced combined multifunctional machine tools are capable of machining these workpieces at higher precision and higher efficiency. As superior machine tools, the demand for combined multifunctional machine tools will increase further in the future. To meet this demand, the researchers and engineers in this field must develop the hardware that helps realize sophisticated functions as well as the supporting software (CAM) to enable advanced control techniques and application technology.

Incidentally, within the next 2 years, the STC-M (Scientific Technical Committee: Machines) of CIRP (The International Academy for Production Engineering) will issue a keynote paper that covers current and future trends in combined multifunctional machine tool technology.

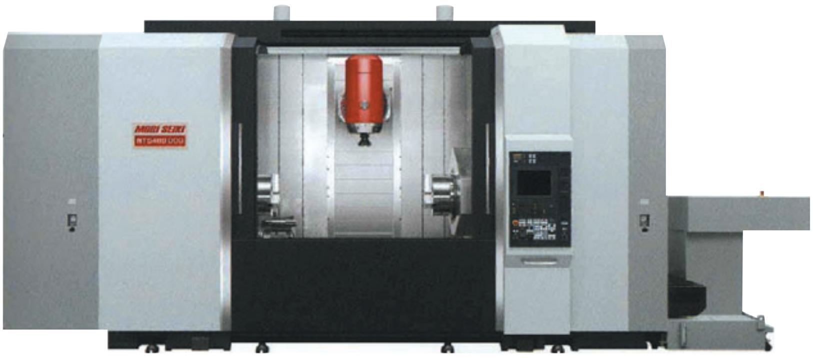

Fig. 3 An example of combined multi-axis machine tool (Mori Seiki Co. NT5400DCG)

4. Ultraprecision Machine Tools

Other than high speed and high efficiency, the most critical requirement for machine tools is high precision. Recently, various ultraprecision machine tools have been developed that are significantly more evolved than earlier high-precision machine tools. Previously, the industrial fields that required ultraprecision machine tools were limited and the market scale for ultraprecision machine tools was relatively small. In contrast, needs have been increasingly mounting for ultraprecision and micro-machined parts and components, such as dies for optical parts and components. In response to this trend, development is in progress for various ultraprecision machine tools.

The background for the needs for ultraprecision machine tools, supporting technologies for their realization and their advantages are summarized in **Table 3**. Progress in the component technologies for ultraprecision machinery, such as air hydrostatic bearings and guides, is remarkable. I believe that advances in hardware technologies for these mechanical elements are contributing to the higher value of Japanese machine tools.

In the field of ultraprecision-machining and micro-machining, typically for the machining of optical parts and components, the requirements for form accuracy and finished surface roughness have always been demanding, and the forms of machined parts and components have become increasingly complicated as summarized in **Table 4**. Also, the process for preparing optical lenses has changed from injection molding with plastic materials to a hot-pressing process with glass. To cope with this trend, an increasingly larger number of dies are being made of materials that are extremely difficult to machine, such as tungsten carbide and ceramics, and these dies must undergo many machining processes including grinding and polishing. These techniques in die machining processes and glass press-forming processes are contributing positively to the manufacture of the lenses on camera cell phones and digital cameras, which are both increasingly common.

Looking more closely at the lenses used in these types of digital equipment, machining processes that are more demanding are necessary to realize their unique optical arrangements. For example, this is needed to create a combination of a Fresnel lens and an aspherical lens, which enhances the optical characteristics of the related optical systems. At the same time, laser printers and other optical equipment that utilize lasers need more sophisticated optical elements that involve nonaxisymmetric or free-curved surfaces. Therefore, needs are growing increasingly for more advanced ultraprecision machining techniques. To this end, I believe that the importance of ultraprecision machine tools needed for ultraprecision-machining and micro-machining will be further highlighted because they are indispensable in machining highly sophisticated parts and components with high added value.

One example of a 3-axis FTS (Fast Tool Servo)[3] device, which is capable of forming a free-curved surface with ultra high precision and higher efficiency, is illustrated schematically in **Fig. 4**. This device, as shown in the diagram, machines a workpiece fixed on a running ultraprecision rotary table while shifting in the radial direction a tool that has its cutting depth in three axial directions controlled at high-speeds and high-response frequencies. If the axial infeed is controlled while the tool is fed in a radial direction, then theoretically any intended shape could be formed on the surface of the workpiece.

In reality, however, it is impossible to form a step square to the cutting direction of a machine tool even at the maximum possible response frequency and response speed of the tool. Therefore, by

Table 3 Background, supporting technologies and advantages of ultraprecision machine tools

Ultraprecision machine tools (ultraprecision cutting/grinding machines)
(Background, supporting technologies)
● Growing needs for ultraprecision and micro-machined parts and components (Optical parts and components, dies, etc.)
● Sophistication of ultraprecision machine elements (main spindles, guideways, feed drive systems, etc.)
● High-precision control technologies
(Advantages)
● Development of new market segments through ultraprecision-machining and micro-machining (Satisfaction of needs) (Optical parts and components, micro parts, mechatronic parts, etc.)

Table 4 Trends in ultraprecision micro machining

1. Form accuracy, finished surface roughness:
- Microns→nanometers

2. Form (in the case of optical parts)
- Spherical surfaces→aspherical surfaces→nonaxisymmetric surfaces→free-curved surfaces

3. Workpiece materials
- Soft metals (aluminum, copper, etc.)
- Hard metals (nickel, hardened steel, etc.)
- Resin materials, anisotropic materials (lithium niobate, fluorite, etc.)
- Brittle materials (tungsten carbide, ceramic materials, etc.)
- Other materials (plastics, etc.)

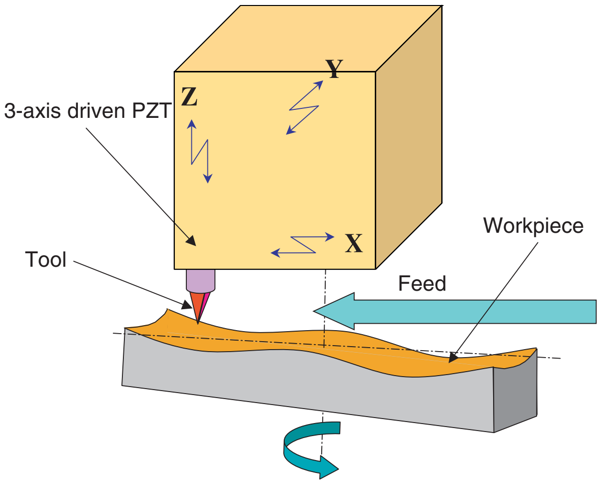

Fig. 4 Schematic illustration of ultraprecision cutting by 3-axix FTS

simultaneously controlling the tool along three axes, the freedom of the machined forms can be increased and the trajectory of motion of the tool being controlled can be simplified. Use of such FTS helps greatly reduce the necessary cutting time on free-curved surfaces.

5. Advanced and Intelligent Control

The increasing sophistication of machine tools is supported by progress in not only hardware but also in software. The background, supporting technologies and advantages of advanced and intelligent control technologies are summarized in **Table 5**. Recently, many advanced (intelligent) control techniques are available that reflect an understanding of machine tool characteristics and machining processes. For example, let us think of a control technique for controlling thermal deformation, which is the most critical factor adversely affecting the machining accuracy of machine tools. A much advanced control technique is now commercially used in which the magnitude of the current thermal deformation is estimated in real-time based on information about the machine tool and temperatures at various spots on the tool. [4] Using this information, the motion of the machine tool is controlled so that higher machining accuracy is ensured under any operating condition.

It is also possible to simulate the motion of the machine tool in real-time based on information about the motion control applied to the machine tool. Utilizing this idea, Okuma Co. has developed an anti-crush system that predicts events such as the crushing of a tool with a chuck and stops the machine as necessary by simulating the motion somewhat in advance of the actual motion of the machine tool. The schematic diagram for this system is illustrated in **Fig. 5**.

Table 5 Background, supporting technologies and advantages of advanced and intelligent control technologies

Advanced and intelligent control
(Background, supporting technologies)
● Need for low-cost controllers with advanced functions
● High-speed, high-precision interpolation systems
● Real-time thermal deformation compensation
● Anti-crush systems that also utilizes simulations
● More advances in computer and IT technologies
(Advantages)
● Greater added value for machine tools
● Evolution of knowledge into established technologies

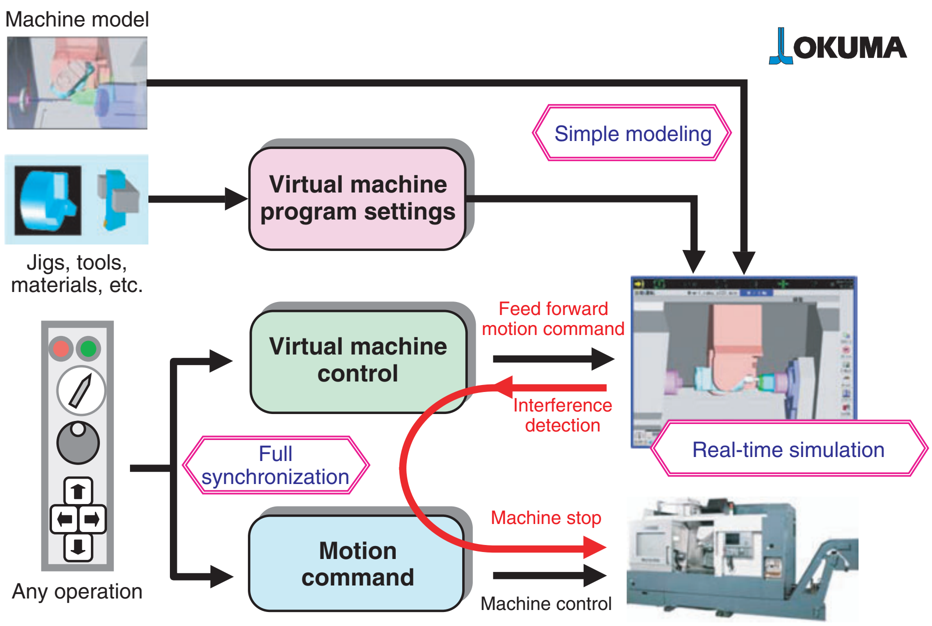

Fig. 5 Conceptual diagram of anti-crush system (Okuma Co.)

In an effort to further advance this idea, under the title of Virtual Machine Tools, the previously mentioned STC-M in CIRP is currently attempting to perform complete simulations that cover machining processes, dynamic characteristics and control characteristics for machine tools.

This simulation scheme is, for example, capable of complete computer simulation of a machine and its processes, allowing it to determine how various components of a machine tool will react when a motion command is given to the machine. It can also determine how the tool and workpiece will interact with each other to machine the workpiece and how the resultant cutting force will affect the machine and tool. The architecture of one example of such a simulation scheme, the virtual CNC system, [5] is schematically shown in **Fig. 6**.

In order to make virtual machine tools become a reality, further research and study efforts need to be made on many issues, including machining processes, and the dynamics and motion characteristics of machine tools. I want to point out that such research and studies are steadily making progress to this end.

6. Conclusion

Based on my own experience, I have described several examples of recent trends in machine tool technologies. The machine tool industry constitutes the backbone of Japan's machinery industry, and for this reason, endeavors to achieve higher speed, higher efficiency and ultraprecision will continue with increasing commitment. In concluding this paper, I want to express my wish that the staff members of **NTN** continue their efforts so that **NTN** technologies and products lead their counterparts in the global machine tool industry in the ever-demanding challenge to achieve the ultra-high-speed and ultra-high-precision required of the main spindle bearings that are critical components of many machine tools.

References

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1966 Graduates Kyoto University Faculty of Engineering, Department of Precision Engineering
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1974 Becomes Assistant Professor of Kobe University Faculty of Engineering
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1985 Becomes Professor of Kobe University Faculty of Engineering (2000～2004 Dean of Faculty of Engineering)

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Select prizes and awards (not all listed)
International Academy for Production Engineering (CIRP) F.W. Taylor medal 1977
Machine Tool Engineering Foundation Encouragement Prizes 1991, 1994, 1995, 1998, 2001
Iue Cultural Prize (Science and Technology Division) (Iue Memorial Foundation) 1998
Japan Society for Precision Engineering Prize 2002, 2003
Hyogo Prefecture Science Prize (Hyogo Prefecture) 2004

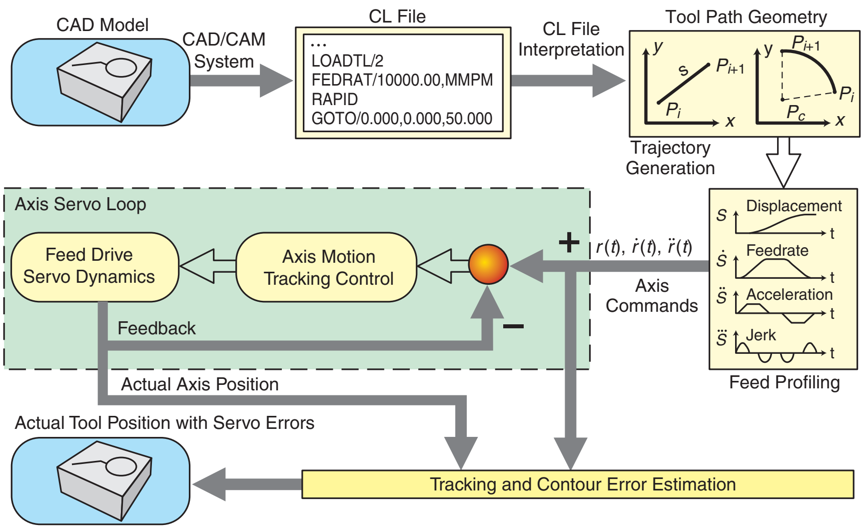

Fig. 6 System architecture of virtual CNC [4]