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Editor

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Machining Dynamics

Fundamentals, Applications and Practices

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Introduction

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1.1 Scope of the Subject

Machining processes are industrial processes in which typically metal parts are shaped by removal of unwanted materials. They are still the fundamental manufacturing techniques and it is expected to remain so for the next few decades. According to the International Institution of Production Research (CIRP), machining accounts for approximately half of all manufacturing techniques, which is a reflection of the achieved accuracy, productivity, reliability and energy consumption of this technique.

Future machine tools have to be highly dynamic systems to sustain the required productivity, accuracy and reliability. Both the machine tool system (Machine/Tool-holder/Tool/Workpiece/Fixture) and machining processes are necessary to be optimized for their usability, cutting performance or the process capability to meet the productivity, precision and availability requirements of the end user. Furthermore, the machine dynamics and machining process dynamics are two indispensably integrated parts which should be taken into account simultaneously in optimizing the machine system, as illustrated in Figure 1.1.

The machining and machine dynamics within the machine system should be well understood, optimized and controlled, because they have the following direct effects:

- They may degrade machining accuracy and the machined surface texture and integrity.
- They may lead to chatter and unstable cutting conditions.
- They may cause accelerated tool wear and breakage.
- They may result in accelerated machine tool wear and damage to the machine and part.
- They may create unpleasant noises and sounds on the shopfloor because of the chatter and vibrations.

A number of analytical and experimental methods have been developed to study the dynamics of the machining system, with the two basic objectives [1, 2]:

(1) to identify rules and guidelines to design stable and robust machine tools, and

(2) to develop rules, models and algorithms for undertaking dynamically stable machining processes in an optimal and adaptive manner.

Machining dynamics are a major factor affecting many production operations, especially high speed machining. Taking account of machining dynamics is particularly important in fine finishing operations, such as grinding, diamond turning, and increasingly, nano/micro machining. As a subject, it is multidisciplinary covering cutting mechanics, tribology, sensor and instrumentation, machine design, tooling, process optimization and control, and manufacturing metrology. The subject combines anayltical and experimental work seamlessly together.

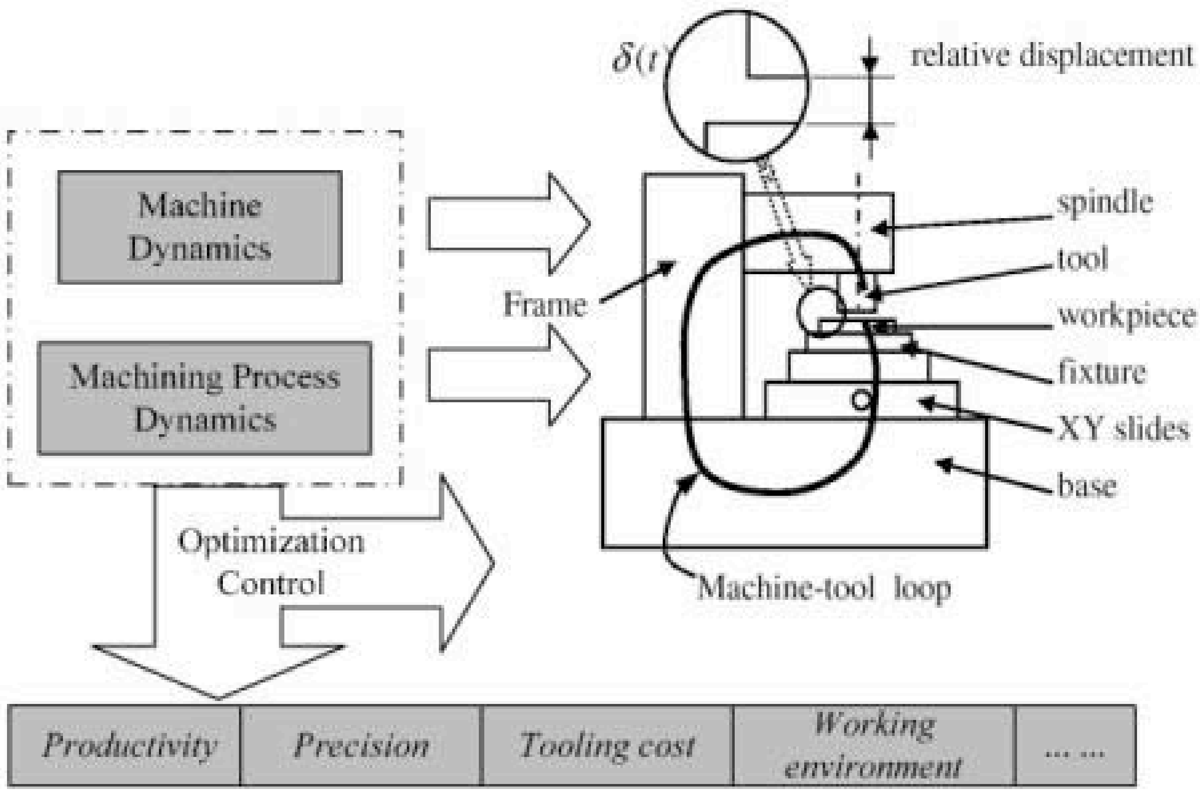

Figure 1.1. The effects of machine and machining dynamics on a machining system

1.2 Scientific and Technological Challenges and Needs

The achievable quality of the precision machined surfaces is affected by four main issues as shown in Figure 1.2. They are the machining process, machine tool performance, workpiece material property and tooling geometry. A scientific approach is needed for building up a theoretical basis to bridge the gap between the surface machined and the determining factors from these four main issues, and to further explore that basis with respect to the desired surface integrity and intended functional performance through machining. It would therefore be of great significance to investigate the fundamentals of high precision surface generation from the manufacturing science viewpoint, which is essential for achieving high precision manufacturing with repeatability, predictability, producibility and productivity. The ultimate goals of manufacturing science and technology are to achieve modelling, simulation, optimization and control of precision machined surfaces including their surface texture, topography, integrity and functionality generation and formation in production processes.

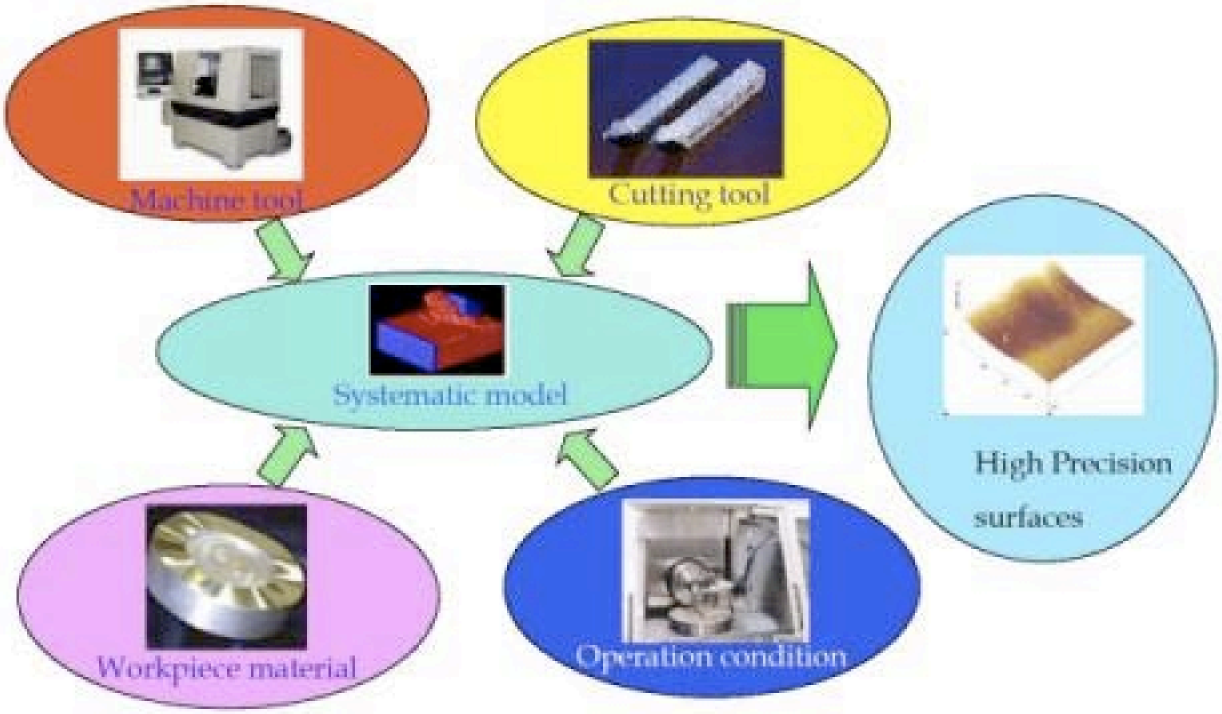

Figure 1.2. Four main issues affecting the precision surface generation

Machining dynamics is the essential and fundamental part for developing the manufacturing science base. They are increasingly important for engaging high speed machining, ultraprecision machining, and nano and micro manufacturing [3, 4, 5].

The advances in computational modelling, sensors, diagnostic equipment and analysis tools, surface metrology, and manufacturing science particularly during the past decade have enabled academia and engineers to research machining dynamics from a new dimension and therefore to have the potential for great industrial benefit, for instance, including:

- Analysis of the material removal dynamics, particularly the effects of cutting speeds and tooling geometry on the stress and temperature conditions at the tool-workpiece interface and thus the surface integrity and functionality.
- Multi-body dynamic analysis of the machine tool structure including the dynamic properties of interfaces between components such as spindles, slideways and drive systems, etc.

- Design of machine tool structures for dynamic repeatability, which is important in predictive control of the machine dynamic performance.
- Dynamic modelling of the machine systems (machine and machining processes) and on line/real time identification of the system modal parameters.
- Development of analytical solutions for the stability of complex contours machining and nonlinear models of interrupted machining.
- Development of novel algorithms (integrated with existing CAD/CAM/CAE tools) for compensation control of machining errors at real time.
- Machining dynamics and micro chatter in ultraprecision machining, and nano and micro cutting.

1.3 Emerging Trends

Increasing demands on manufacturing precision products require the development of precision machines for engaging high value manufacturing. A trend in developing precision machines is that machine tool developers are expected to not only concentrate on the optimization of the machine tool itself in terms of maximum speeds and acceleration of machine axes, but to also take full account of machining dynamics in processes. Therefore, when designing precision machines, it is essential to consider the mechanical structures, control system dynamics, and machining process dynamics simultaneously [6, 7]. An integrated dynamics-driven approach is highly needed for designing precision machines as illustrated in Figure 1.3.

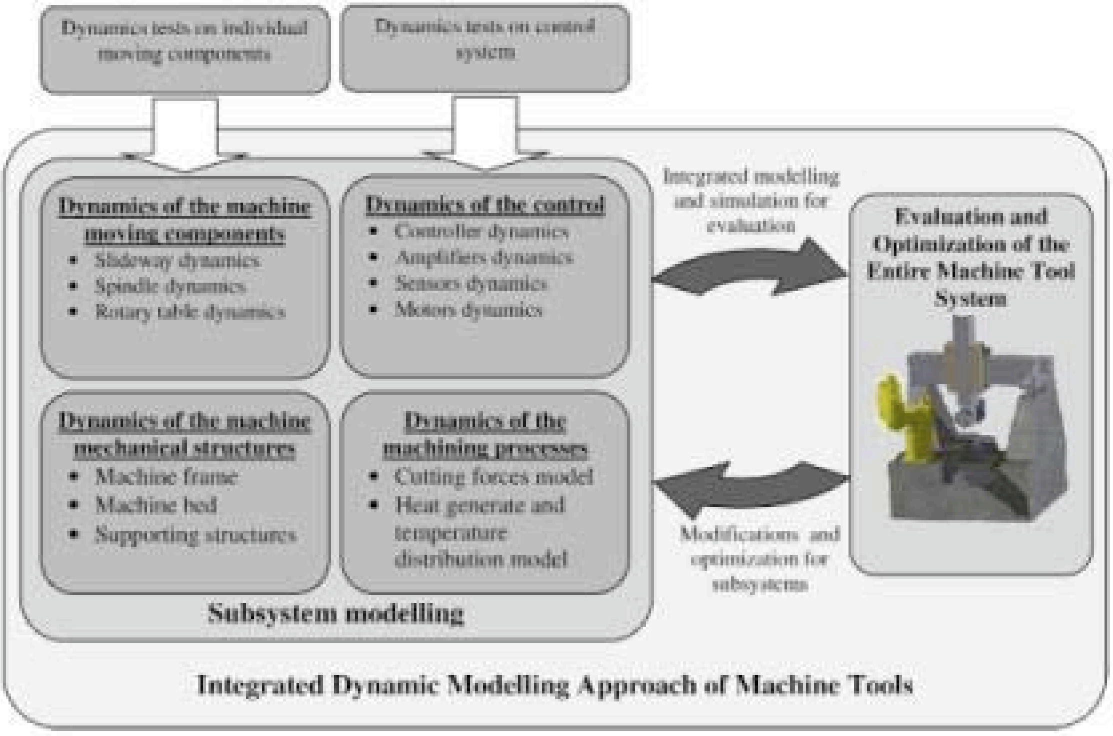

Figure 1.3. Schematic of the integrated dynamics-driven machine design approach

High-accuracy mechanical miniaturized components with dimensions ranging from a few hundred microns to a few millimetres or features ranging from a few to a few hundreds of microns are increasingly in demand for various industries, such as aerospace, biotechnology, electronics, communications, optics, etc. [8]. Advanced high precision machines have the unique advantage of manufacturing high-end miniaturized components in terms of the accuracy, surface finish and geometrical complexity in a wide range of engineering materials. Nevertheless, the micro and functional features on the machined surfaces are becoming dominant particularly for the miniature and micro components and products. Therefore, the detailed and in-depth understanding of the intricate relationships among machines, processes, tooling and materials are increasingly demanded and indispensable for implementing high precision and nano/micro manufacturing. As illustrated in Figure 1.4, machining dynamics driven modelling and simulation can be utilized as the commencing point to comprehensively investigate the complex relationships and phenomenon including:

- Prediction of the surface texture, integrity and functionality generation in machining processes.
- Optimization and control of machining processes against the functionality and performance requirements of the components and products.
- Implementation of the industrial-feasible control algorithms for engaging intelligent, adaptive and high throughput manufacturing.

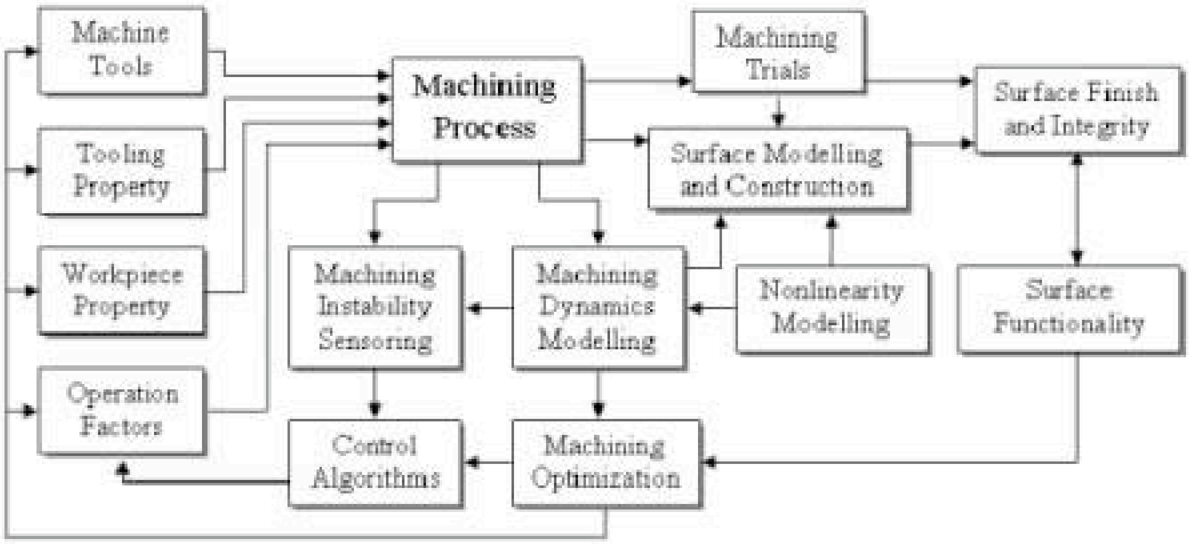

Figure 1.4. Modelling, simulation, optimization and control of the machining process based on machining dynamics

Finite Element Analysis (FEA) is the most practically useful approach for analyzing machining systems because it can be used not only for dynamics analysis, but also for static and thermal analysis. In more recent practice, automeshers using either tetragonal or cubic elements have been increasingly applied because the machining process and associated machining system are the truly dynamically changing process and system and the meshers should thus adaptively change accordingly. Furthermore, multiscale modelling based on combining FEA, micro-mechanics or molecular dynamics (MD) is being used for modelling the formation of surface integrity such as surface roughness, residual stress, micro hardness, microstructure change and fatigue. Throughout the past decade, there have been tremendous research and development for achieving the ultimate goals as illustrated in Figure 1.4 [9, 10, 11, 12], although it would be a continuous long-lasting process.

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