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Current Status and Development of Intelligent Cutting Technology: A Review

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Abstract. With the deepening development of Industry 4.0 and intelligent manufacturing technology, intelligent cutting technology is becoming the core productivity in the fields of high-quality machining and advanced manufacturing. In this article, the relevant technical system, aplication and future challenges of intelligent cutting were systematically outlined, which demonstrated the autonomous optimization mechanism of the cutting process through software data-driven and hardware electromechanical collaboration. At present, intelligent cutting systems can significantly improve machining accuray, efficiency and sustainability by integrating multi-source information preception with electronmechanical automation systems. However, anisotropism processing for different objects, delayed upgrades of core components and algorithm generalization remain main technical bottlenecks. In the future, intelligent cutting will focus on breakthroughs in cross-platform standardized protocols, metamaterial machine tool structures and sensing technology. This review provided a theoretical framework and technical path for the research and industrialization of intelligent cutting.

Keywords: Cutting, Intelligent monitoring, Cutting tool

1. Introduction

With the continuous competition in the globalized manufacturing industry, cutting process, as a key technology in mechanical manufacturing, has become a high ground for improving the competitiveness of the manufacturing industry through intelligent upgrading. Traditional cutting techniques are limited by experience-driven parameter selection, error compensation and other factors, which makes it difficult to meet the demands of complex precision parts machining in fields like aerospace and military industry. According to statistics [1], the scrap rate caused by flutter in the machining of aircraft engine blades exceeds 10%. Intelligent cuttting provides solutions to the above problems through artificial intelligence (AI) and advanced sensing technology.

The intelligent cutting technology system can be divided into the following three layers:

• Operation layer: multi-dimensional capture of machining status is achieved through iterative hardware upgrades.

• Perception layer: analyzing the status of processing machines through sensors to provide a data foundation for equipment monitoring and maintenance.

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• Execution layer: making corresponding equipment maintenance and action based on sensor data.

Breakthrough achievements of recent years in intelligent cutting include: the chatter suppression algorithm developed by IPT (German) could reduce thin-wall machining vibration by 60% [2]. GE Aviation used Kistler cutting force sensor (9129AA) to process engine titanium alloy blades, which could reduce the machining cycle by 33% and improve the accuracy from ±25μm to ±8μm [3]. Sandvik has developed a CoroPlus intelligent tool holder which integrates a three-way piezoeletric force sensor and a wireless transimission module, which could predict the remaining tool life through LSTM with an error of less than 3% [4].

Today's intelligent cutting technology faces three major challenges:

(1) Real-time decision-making challenges: Decision-making delays caused by signal fusion processing latency; (2) Hardware computing power limitations: Conflict between the high computational load of AI and the limited resources of equipment; (3) Industrial compatibility issues: Mismatch between high-cost equipment and enterprise requirements.

This research advances an intelligent cutting technology framework. Delineates performance boundaries attainable through diverse intelligent solutions, and empirically validates the system via industrial machining case studies.

1.1. Cutting tools

Conventional tooling systems exhibit limited durability, necessitating frequent manual inspection. Automated monitoring solutions address this limitation through methodologies such as strain gauge placement determined via load path analysis and experimentally validated through static compression testing.Figure 1 illustrates force-strain curves for six gauges at distinct positions and orientations, revealing variations in gradient magnitude and hysteresis behavior for an initial prototype. Positions 1 and 5, exhibiting optimal characteristics, were selected for subsequent development stages. Beyond force measurement, temperature monitoring at the indexable inserts served as a critical parameter for enhanced wear detection. Type K thermocouples were deployed adjacent to both the cutting inserts and strain gauges. This configuration ensured sensor operation within permissible temperature limits while simultaneously enabling precise measurement of thermal gradients between the strain gauges and tool holder. Furthermore, an integrated MEMS accelerometer and position sensor monitored rotational speed, vibrational signatures, and impact events.

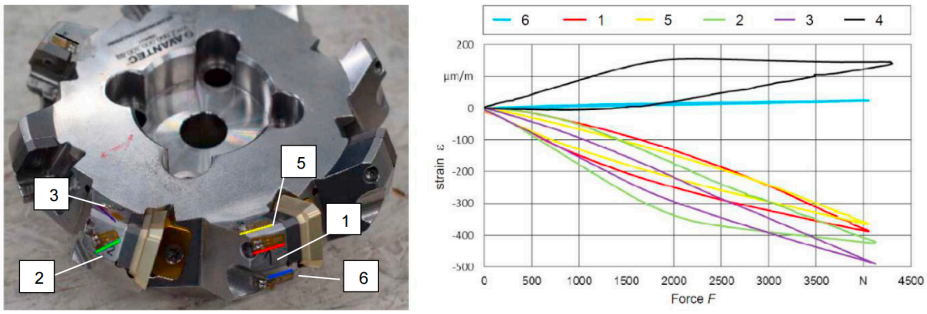


Figure 1. Automatic tool caring system [5]

Cutting tools are subjected to high stresses by modern machining technologies, like dry machining, high-speed machining or high-performance machining. The development of new

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processes demands adapted cutting tools. An ideal cutting material combines high hardness with good toughness and chemical stability. In order to merge the characteristics mentioned, wear resistant coatings with a tough substrate material are combined. A total coating thickness between 3-10 vm is appropriate, whereby the combinations and sequences depend on the application.

The substrate-layer compound fails due to thermal and mechanical loads in dry machining. Failures occur in particular if the substrate itself reaches a critical load. The failures of the compound are strongly influenced by the surface and subsurface characteristics of the ground tool. The surface and the subsurface characteristics of the tool are a direct result of the grinding operations used during the tool manufacture [6]. Requirements for the roughness of cutting tools are shown in Figure 2.

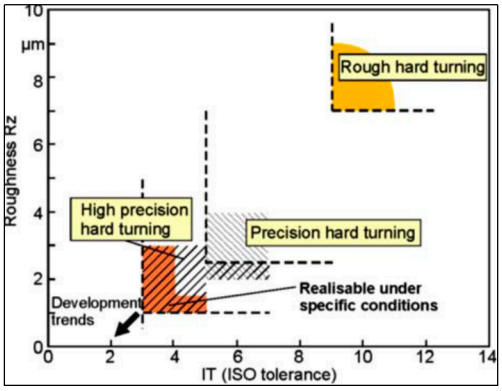


Figure 2. Requirements for roughness of cutting tool [6]

1.2. Lathe

When machining titanium alloys, the complex aerodynamic surfaces of aircraft engines can significantly reduce the average tool life. To address this issue, the DMG MORI NTX 1000 turn-mill center (Figure 3) is employed. Its software enables real-time synchronous monitoring of cutting force, temperature, and vibration data with a latency of less than 5ms, thereby minimizing equipment errors and damage [7].

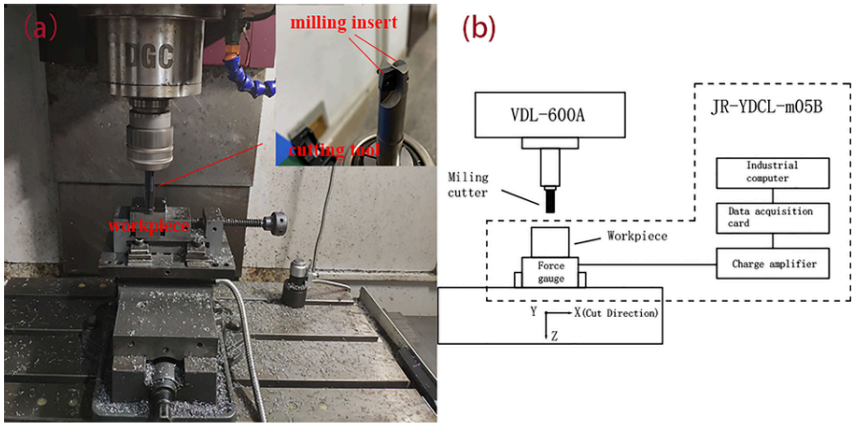


Figure 3. Processing mechanism

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2. Monitoring intelligence

2.1. Flutter

The productivity of machine tools is often limited due to chatter vibrations caused by relative displacements between the tool and the workpiece. With some certain additional highly dynamic axes near the tool center point, the active workpiece holder offers possibilities to prevent chatter vibrations. Through the controlled axis of AWH, a stable cutting depth of 4.5 mm can be achieved, while without control, the stability is limited to 3.0 mm. Due to the application of active workpiece fixtures, performance has been improved by 50% [8]. Figure 4 shows an example of Surface measurements with an active workpiece holder.

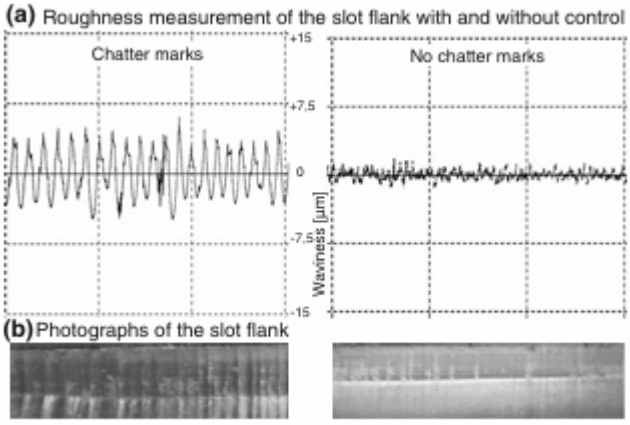


Figure 4. Surface measurements with active workpiece holder [8]

2.2. Cutting force

In metal cutting operations, implementing an effective monitoring system relying on suitably developed algorithms or schemes preserves machine tool integrity and mitigates premature tool wear. This work proposes a fault detection and diagnosis approach founded on an observer model for uncertain linear systems. Utilizing the derived uncertain linear model, a robust observer is constructed, illustrated in Figure 5, generating essential system information. This observer subsequently functions as a state estimator for tool wear, while fault detection leverages the observed variables in conjunction with cutting force measurements [9].

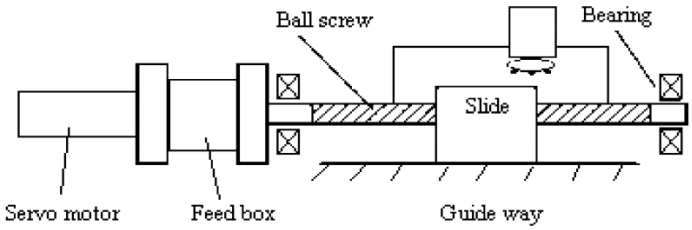


Figure 5. A feed-drive system [9]

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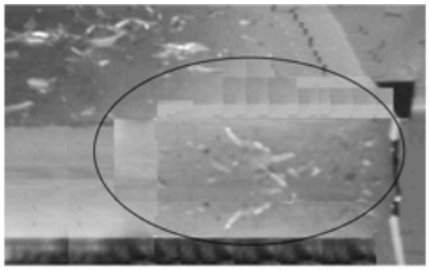
2.3. Cutting temperature

Owing to the dominance of two primary wear mechanisms—adhesive wear and attrition—diamond-based cutting tools represent the sole economical alternative for machining these materials. Tool degradation stemming from tribochemical interactions remains notably low under these conditions, attributable to the modest temperatures generated during machining (AlSi7Mg melt temperature range: 557–613°C). Likewise, when machining high-silicon aluminum alloys, CVD diamond-coated tools deliver extended service life owing to the absence of a binding phase [6].

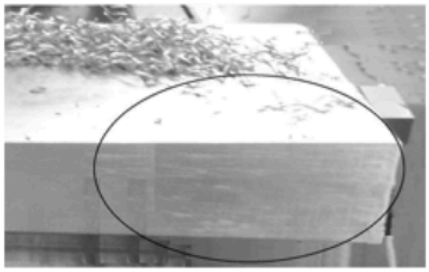
3. Software intelligence

3.1. Algorithms

Milling chatter can damage workpiece surface quality, reduce cutting efficiency, and shorten the service life of tools and machine tool spindles. To achieve online suppression of milling chatter, real-time Fast Fourier Transform (FFT) technology can be employed to rapidly extract the frequency-domain characteristics of chatter and make accurate judgments. This ensures the surface roughness in chatter-prone zones remains below 2 μm, thereby establishing a dynamic monitoring mechanism for chatter trajectories. In figure 6, (a) and (b) respectively shows the cutting effect on workpieces machined without and with chatter suppression.



(a) Partial enlarged view of workpiece surface chatter



(b) Partial enlarged view of workpiece surface after chatter suppression

Figure 6. Comparison of cutting effects on workpieces machined with and without online chatter suppression [10]

3.2. Cutting trajectory

Complicated surface processing represents a critical yet challenging task within the mechanical manufacturing industry. This paper introduces an enhanced trajectory planning algorithm for impeller surface machining utilizing a 6-DOF cutting robot. For example, a single finished toolpath on an impeller blade integrates cutter feedrate, bow height error, and cutter pose

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(position/orientation) via B-spline interpolation to generate the optimal cutting trajectory. Following this trajectory planning phase, the optimal motion profiles for the 6-DOF robot's joints are computed. This process enables seamless transitions in robot feedrate and trajectory while adaptively regulating joint movements. Current cemented carbide impeller production relies heavily on five-axis machining centers. Though ideal for high-precision applications, these systems incur substantial costs. Multi-DOF industrial robots demonstrate superior cost-effectiveness for machining complex-surface components with moderate hardness and precision tolerances. Compared to five-axis centers, 6-DOF cutting robots provide greater maneuverability in tool positioning and streamline complex trajectory execution. Consequently, they enable economically viable machining of qualifying workpieces where accuracy requirements permit [11].

*Note: B-spline interpolation (previously detailed) facilitates smooth trajectory transitions through curvature and bow height error-*constrained *feedrate adaptation.*

4. Conclusion

Through this paper, it can be observed that intelligent cutting technology has achieved significant advancements in the following aspects:

1. Performance breakthroughs through technological integration: Intelligent algorithms have reduced chatter-induced surface roughness to below 2 μm and established a dynamic chatter monitoring mechanism.

2. Enhanced responsiveness via monitoring key technologies: By monitoring the machining process of low-temperature metals (melting point ≈600°C), tool lifespan has been effectively extended.

Moving forward, the focus of intelligent cutting should be on:

1. Developing multi-sensor fusion models to overcome limitations imposed by single-variable constraints.

2. Creating intelligent collaborative platforms to enable cross-regional equipment coordination.

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