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Research and Optimisation of Key Issues in the Milling Process of Difficult-to-Machine Materials

Yan Zeng, Yang Luo

Engineering Training/Student Innovation Practice Centre, Chengdu Technological University, Chengdu, Sichuan 611730, China

Abstract

This paper systematically analyses the machining performance and mechanisms of difficult-to-machine materials such as austenitic stainless steel, titanium alloys, and pure metals during milling processes. It addresses issues including low cutting efficiency, rapid tool wear, and challenges in ensuring machining accuracy. By analysing material properties and machining challenges, this paper focuses on comprehensive process improvement measures encompassing tool selection, geometric parameter optimisation, cutting parameter setting, and cooling strategies. Aimed at providing theoretical foundations and practical guidance for the efficient and precision milling of the aforementioned typical difficult-to-machine materials.

Keywords

Difficult-to-machine materials; Milling; Analytical processing.

1. INTRODUCTION

Against the backdrop of sustained development in the manufacturing sector, difficult-to-machine materials such as austenitic stainless steel, titanium alloys, high-temperature alloy steels, and certain pure metals are finding increasingly widespread application in mechanical components and various types of moulds. However, such materials commonly exhibit low machining efficiency and severe tool wear during cutting processes, presenting a critical bottleneck that constrains both machining quality and productivity [1]. Among various machining methods, milling-as a predominantly employed process-faces the aforementioned challenges. To effectively address these difficulties and enhance milling efficiency, it is imperative to systematically analyse the physical and mechanical properties of difficult-to-machine materials and master applicable process improvement measures. On this foundation, the geometric parameters of milling cutters and cutting parameters must be judiciously selected. This approach ensures part machining accuracy while extending tool use-time, thereby meeting increasingly demanding machining requirements.

The primary physical properties of difficult-to-machine materials for cutting operations include: Hardness exceeding 250 HB, Strengthσ_b>0.98GPa, Elongationδ>98,000J/m^2, Thermal conductivity k<41.9W/(m·°C) [2].

2. CHARACTERISTICS OF MILLING DIFFICULT-TO-MACHINE MATERIALS

During milling operations, the machined material is influenced by factors such as the milling cutter's structure and material, different milling methods including climb milling and conventional milling, and the chip evacuation method employed during the process. Consequently, milling difficult-to-machine materials exhibits the following characteristics:

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Milling temperature. When machining difficult-to-cut materials, cutting temperatures are generally elevated. When forming milling cutters with minimal rake angles are employed for workpiece machining, the difficulty of cutting initiation and increased cutting resistance result in heightened cutting temperatures; Materials with high thermal strength, such as high-temperature alloys, exhibit continuously increasing tensile strength at temperatures between 500 and 800°C. This increases the resistance encountered by the milling cutter when penetrating the workpiece, thereby generating greater cutting heat; The low thermal conductivity of the material impedes heat dissipation during milling operations. Furthermore, during conventional milling, the contact friction between the tool's rake face, flank face and the workpiece also contributes to elevated cutting temperatures [3].

Plastic deformation and work hardening during milling. The deformation coefficient of most difficult-to-machine materials is substantial, such as austenitic stainless steels and high-temperature alloy steels. When the milling speed reaches 50mm/min, the deformation coefficient begins to increase; at approximately 600mm/min, the deformation coefficient reaches its maximum value [4]. Due to the generally high cutting speeds employed during milling operations, both the cutting surface and the machined surface undergo significant plastic deformation. Consequently, work hardening occurs in the material. For instance, when machining difficult-to-cut materials such as austenitic stainless steels and high-temperature alloy steels, the degree of work hardening is several times greater than when machining 45 steel, resulting in a corresponding increase in cutting resistance.

When milling difficult-to-machine materials, the resulting milling forces far exceed those encountered with ordinary carbon steel. This phenomenon primarily stems from the material's high strength and significant plastic deformation characteristics, which in turn generate substantial cutting resistance and high thermal loads. Ultimately, this leads to high power consumption during the milling process and elevated tool loading.

During the milling of difficult-to-machine materials, rapid tool wear and a significant reduction in tool life represent one of the core challenges. This is primarily attributable to two factors: firstly, the material exhibits a pronounced tendency towards work hardening, and secondly, the milling zone reaches extremely high temperatures. These factors collectively exacerbate diffusion wear and oxidation wear on both the rake and flank faces of the cutting tool；Secondly, such materials produce tough chips that readily exhibit adhesion and fusion welding at the cutting-edge region. This not only impedes normal chip evacuation but may also cause abnormal tool damage (such as edge chipping or tool breakage) due to chip blockage.

Given the aforementioned machining challenges, targeted process improvements are essential to ensure both machining efficiency and cost-effectiveness when milling difficult-to-machine materials.

3. IMPROVEMENT MEASURES FOR MILLING DIFFICULT-TO-MACHINE MATERIALS

3.1. Selecting the Appropriate Tool Material

The selection of tool materials is crucial for ensuring machining efficiency and quality, based on the milling characteristics of difficult-to-machine materials. The selected tool should combine high wear resistance, good toughness, high thermal conductivity, and excellent high-temperature mechanical properties [5]. Taking the milling of high-strength steel as an example, tool materials may include high-performance high-speed steel and various types of cemented carbide; under conditions permitting high-speed cutting, ceramic tools also represent an ideal choice.

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3.2. Appropriate Milling Cutter and Geometric Parameters

Optimising the geometric parameters of milling cutters through regrinding is an effective approach to enhancing machining performance, tailored to the specific processing characteristics and requirements of the material. When milling materials with lower hardness and excellent plasticity, appropriately increasing the tool's rake angle and clearance angle can reduce cutting resistance and improve chip evacuation. Conversely, when machining high-temperature alloys-which exhibit high deformation resistance, pronounced work-hardening tendencies, and elevated cutting forces-employing larger cutting-edge inclination and helix angles is advisable. This approach enhances edge strength, improves cutting stability, and optimizes heat dissipation conditions.

3.3. Selecting Appropriate Milling Parameters

In the milling process of difficult-to-machine materials, the judicious selection of milling methods constitutes a critical process decision for optimising the cutting operation and enhancing both machining efficiency and quality. Based on the relative relationship between the milling cutter's rotation direction and the workpiece feed direction, peripheral milling can be categorised as climb milling and conventional milling; whereas according to the milling approach form, end milling can be classified as symmetrical milling or asymmetrical milling [6]. Given the characteristics of difficult-to-machine materials, the scientific selection of milling methods is paramount. During climb milling, the cutting speed direction of the milling cutter aligns with the workpiece feed direction, with the cutting thickness of the cutter teeth decreasing from maximum to zero. This approach minimises impact during engagement, thereby suppressing cutting vibrations, extending tool life, and enhancing surface finish quality. Concurrently, the cutting forces press the workpiece against the worktable, contributing to improved clamping stability.

Therefore, provided machining rigidity permits and the machine tool feed mechanism exhibits zero backlash, climb milling is the preferred method for machining difficult-to-cut materials, effectively mitigating work hardening phenomena. During Conventional milling, the cutting speed direction of the milling cutter runs counter to the workpiece feed direction. Prior to engagement, the cutter teeth must slide a certain distance across the already hardened surface. This not only accelerates tool wear but also tends to deepen the work-hardened layer. Given the pronounced tendency towards work hardening in difficult-to-machine materials, conventional milling should be avoided wherever possible, unless the machining system exhibits significant radial clearance or is employed for roughing hard-skinned forgings or castings.

The workpiece is positioned on the milling cutter's centre line, with symmetrical chip thickness during both entry and exit. This method generates substantial radial cutting forces, readily inducing vibration, and is generally not recommended for process systems with poor rigidity. Asymmetric milling encompasses asymmetric climb milling and asymmetric conventional milling. During asymmetric climb milling, the chip thickness at tool entry is greater than at exit, resulting in reduced entry impact force and a smoother cutting process. This effectively minimises work hardening and improves tool wear. Therefore, asymmetric climb milling is recommended for materials prone to work hardening, such as titanium alloys and high-temperature alloys. Asymmetric conventional milling, however, should be employed with caution as the thin chips produced during the initial cut and the tendency for slippage can accelerate tool wear.

3.4. Selecting the Appropriate Milling Method

For milling general materials, Conventional milling is predominantly employed. However, for materials exhibiting significant plastic deformation and pronounced work hardening

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characteristics, climb milling should be adopted [7]. During climb milling, chip adhesion is reduced, resulting in lower pressure on the tool's rake face. Consequently, conventional milling enhances cutter longevity and achieves a lower surface roughness value R_0.

3.5. Selecting the Appropriate Cutting Fluid

In selecting cutting fluids, compatibility with tool materials is essential: when employing high-speed steel milling cutters, water-soluble cutting fluids are advisable to maximise their cooling efficacy.

Conversely, when milling with carbide end mills, oil-based extreme pressure lubricants are recommended. These form a lubricating film at elevated temperatures, effectively reducing tooth adhesion and diffusion wear.

Beyond optimising cutting tools and coolants, the rigidity of the machine tool system and its accessories is equally critical. Vibrations during machining can be suppressed by adjusting the lead screw nut clearance in the worktable feed system. Concurrently, employing high-rigidity, high-hardness tool holders and fixtures effectively enhances the overall stability of the process system, thereby ensuring machining accuracy and surface finish quality.

4. MILLING OF TYPICAL DIFFICULT-TO-MACHINE MATERIALS

4.1. Austenitic Stainless Steel

Austenitic stainless steels generally exhibit lower hardness and strength, yet possess high elongation and impact toughness-three times that of 45 steel. Their thermal conductivity is low, amounting to only one-third of 45 steel. They suffer significant high-temperature hardening, generating high temperatures during milling, presenting challenges in chip breaking, and exhibiting considerable vibration [8]. Consequently, the system rigidity of the machine tool, fixture and cutting tool must be high. The milling cutter should have fewer teeth, and climb milling is preferable. A cutting fluid with excellent cooling properties, such as fluidized oil or emulsion, should be injected to form a protective film at high temperatures and reduce tool adhesion.

Austenitic stainless steel is a common difficult-to-machine material. The milling cutter geometrical parameters and machining parameters applicable during milling are shown in Tables 1 and 2.

Table 1. Milling cutter geometry parameters for machining austenitic stainless steel [11]

Angle name	Angle value	
	High-Speed Steel Milling Cutter	Carbide-tipped milling cutter
Front corner γ_0	10°~20°	5°~10°
Clearance angle α_0	Face Mill: 10°~20° End mill: 15°~20°	Face Mill: 5°~10° End mill: 12°~16°
End tool nomal clearance α'_0	6°~10°	4°~8°
Tool cutting-edge angle k_r	60°	60°
End cutting-edge angle k'_r	1°~10°	1°~10°
helix angle β	End mill: 35°~45° Roughing end mill: 15°~20°	End mill: 5°~10°

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Table 2. Milling cutting parameters for machining austenitic stainless steel [11]

Types of Milling Cutters	Tool materials	Milling speed (m/s)	Feed speed (mm/s)
End mill	High-speed steel	0.25~0.33	0.5~1.25
	Cemented carbide	0.67~1.67	0.5~1.25
Roughing end mill	High-speed steel	0.30~0.42	0.75~1.25
Saw blade, Three-sided milling cutter	High-speed steel	0.58~0.83	0.33~1
	Cemented carbide	0.83~1.83	0.33~1
Face mill	Cemented carbide	1.00~2.50	0.5~2.5

4.2. Titanium Alloy

Titanium alloys have found extensive application in aerospace, medical devices and other fields owing to their high specific strength, excellent corrosion resistance and superior biocompatibility. However, these excellent properties also render it a typical difficult-to-machine material. Titanium alloys exhibit minimal elongation and impact toughness, resulting in low plastic deformation and a small deformation coefficient during machining. They possess poor thermal conductivity yet high strength and hardness. Typically, YG-grade cemented carbide milling cutters, such as YG10H and YG6, are employed for milling operations [9]. Among these, YG10H exhibits favourable wear resistance and hardness, making it suitable for rough milling operations on titanium alloys; YG6 is suitable for precision milling operations, yielding satisfactory results. The selection of milling cutter geometry parameters is as follows: the rake angle is typically set between 0°and 5°, the clearance angle between 4°and 10°, and the main cutting-edge angle: between 45°and 75°. Milling speeds should not be excessively high, generally ranging from 20 to 83mm/s. High-speed steel milling cutters include end mills, cylindrical cutters, and form cutters. When the cutting allowance is substantial, cobalt-alloyed high-speed steel cutters may be employed. To mitigate tool wear during milling, climb milling should be employed. Cutting speeds are typically low (15mm/s), and extreme pressure cutting fluids should be flushed during machining. Given titanium alloys' considerable elastic deformation, machine rigidity must be high to prevent cutting vibrations. Workpiece clamping force should not be excessive, and auxiliary supports may be utilised to enhance milling accuracy.

4.3. Milling of Pure Metallic Materials

Commonly used pure metals include copper and pure aluminium, which possess relatively low hardness and strength but high thermal conductivity, making them favourable for machining operations; However, it exhibits high plasticity, significant deformation, a tendency to stick to cutting tools, difficulty in chip breaking, substantial cutting forces, and challenges in achieving a satisfactory machined surface finish. Given these machining characteristics, high-speed steel tools are generally employed for machining pure metals. When selecting milling cutter geometry parameters, a large rake angle of 20° to 25°, a clearance angle of 12° to 25°, and a tool cutting-edge angle of 45° to 90° should be adopted. Additionally, a sharp cutting-edge should be ground to minimise chip deformation. Higher cutting speeds and greater cutting depths should be employed wherever possible [10]. To achieve lower surface roughness values, cutting fluid may be applied to the machined surface of the workpiece.

Figure 1 depicts a milling cutter employed for machining aluminium. It comprises a disc 1 fabricated from structural steel and brazed carbide inserts 2. Cutting chips enter the clearance space 5 between inserts 3 and 4, preventing accumulation and jamming. The radial length of the inserts varies from 20 to 300millimetres, enabling the milling of deep grooves.

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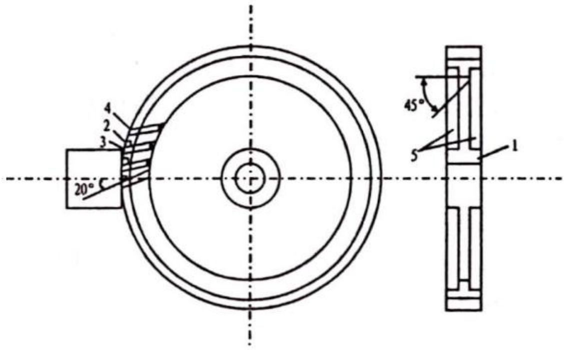

Figure 1. Two-dimensional diagram of a milling cutter for machining aluminiu [12]

5. CONCLUSION

The process improvement measures discussed above for several typical difficult-to-machine materials stem from the synthesis and refinement of extensive machining practice. However, as modern industry continually elevates its demands on product performance and material compositions undergo ongoing optimisation, novel high-performance engineering materials will inevitably emerge. This signifies that milling technology for difficult-to-machine materials faces an enduring need for evolution, with its machining mechanisms, tooling technologies, and process strategies still requiring further in-depth research and development.

This paper systematically investigates key issues encountered during the milling of typical difficult-to-machine materials such as austenitic stainless steel, titanium alloys, and pure metals. These challenges include elevated cutting temperatures, pronounced plastic deformation and work hardening, substantial milling forces, and rapid tool wear. Through analysis of the cutting characteristics and failure mechanisms of these materials, comprehensive process improvement measures are proposed. These centre on tool selection, optimisation of geometric parameters, rational setting of milling parameters, and cooling lubrication strategies.

Research indicates that adopting tailored machining processes according to material properties is pivotal to enhancing processing efficiency. For austenitic stainless steel, emphasis should be placed on improving process system rigidity, employing low-tooth-count milling cutters with climb milling techniques, and implementing efficient cooling; For titanium alloys, suitable YG-type cemented carbide tools should be selected, employing a smaller rake angle and low-speed climb milling strategy, while strictly controlling vibration and clamping deformation during machining. For pure metals, large rake angles, sharp cutting-edges, and high-speed, deep-cut parameters should be utilised to suppress tool adhesion and plastic deformation, thereby improving surface finish.

In summary, the efficient and precise milling of difficult-to-machine materials constitutes a systematic engineering endeavour, whose optimisation outcomes depend upon the coordinated regulation of material properties, tooling technology, cutting parameters and cooling conditions. The process principles and practical data reviewed herein provide both theoretical foundations and practical references for the milling of relevant materials. Looking ahead, as new materials continue to emerge and demands for machining efficiency, quality and environmental sustainability intensify, research into milling techniques for difficult-to-machine materials will advance to greater depths. Subsequent studies will focus on the following directions:

Development and Application of Novel Tool Materials: Such as customised nano-coatings and gradient-structured tools tailored for specific materials.

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Intelligent Milling and Adaptive Control: Leveraging big data and artificial intelligence, develop an intelligent milling system capable of real-time perception of machining conditions and adaptive adjustment of process parameters.

Advancing Green Manufacturing Technologies: Further exploring the limits and application boundaries of technologies such as dry cutting and low-temperature cooling, driving the transition towards fully green processing for difficult-to-machine materials.

Multiphysics Coupling Modelling and Simulation: Establishing a more precise multiphysics coupling model for the milling process to provide more reliable theoretical guidance for process optimisation.

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