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ANALYSIS OF THERMALLY ASSISTED MACHINING TECHNOLOGIES FOR DIFFICULT-TO-CUT MATERIALS (A REVIEW)

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Abstract. This paper presents a comprehensive review of thermally assisted machining (TAM) methods for difficult-to-machine materials, including titanium alloys, high-strength steels, and superalloys. The study analyzes the fundamental principles of TAM, which involve localized heating of the workpiece to reduce its strength and improve machinability. The main focus is on laser-assisted, induction-assisted, and hybrid machining methods. It is shown that the application of thermal energy significantly reduces cutting forces, tool wear, and surface roughness, while improving process stability and machining efficiency. Special attention is given to the influence of temperature on material behavior and surface quality.

A comparative analysis of different TAM techniques is carried out based on recent experimental and numerical studies. The results indicate that laser-assisted machining provides high precision and localized heating, induction heating ensures uniform temperature distribution, and hybrid methods offer improved performance due to combined effects. It is concluded that the effectiveness of TAM strongly depends on the optimal selection of process parameters, particularly temperature. Excessive heating may negatively affect material properties, while controlled thermal input leads to significant improvements in machining performance. The findings of this review highlight the significant potential of (TAM) technologies and their broad applicability in advanced industrial manufacturing processes, particularly in the machining of difficult-to-machine materials.

Keywords: thermally assisted machining, laser-assisted machining, induction heating, difficult-to-machine materials, cutting forces, surface roughness

Introduction. In modern engineering industries, including aerospace, energy, and advanced manufacturing, there is an increasing demand for materials with superior mechanical and functional properties such as high strength, wear resistance, and thermal stability. Materials such as titanium alloys, high-strength steels, and nickel-based superalloys are widely used due to their excellent performance under extreme conditions. However, these materials are classified as difficult-to-machine due to their high strength, low thermal conductivity, and tendency to work harden during machining processes [1], [2], [4].

The machining of such materials is associated with several critical challenges, including high cutting forces, rapid tool wear, and poor surface quality. In addition, excessive heat generation in the cutting zone leads to increased thermal loads on both the cutting tool and the workpiece, which negatively affects dimensional accuracy and tool life [4], [5], [9]. To overcome these limitations, alternative machining techniques have been actively developed in recent years. One of the most promising approaches is thermally assisted machining (TAM), which involves preheating or simultaneous heating of the workpiece to modify its mechanical properties and improve machinability [2], [6], [8].

The application of external heat sources, such as laser radiation, induction heating, plasma, or gas flame, enables localized reduction of material hardness and enhancement of its plasticity in the cutting zone. As a result, cutting forces are reduced, tool wear is minimized, and surface quality is improved [6], [8], [10]. Numerous studies have demonstrated that TAM significantly enhances machining efficiency, reduces production costs, and extends tool life when processing difficult-to-machine materials. Furthermore, hybrid techniques combining thermal and ultrasonic assistance have shown improved process stability and superior surface integrity compared to conventional machining methods [2], [7], [9].

Therefore, a comprehensive analysis of existing thermally assisted machining methods and their comparative evaluation is of great importance for improving the efficiency of modern manufacturing processes. This paper aims to review the main TAM methods, their characteristics, and their influence on the machining performance of difficult-to-machine materials.

Analysis of Thermally Assisted Machining Methods. Thermally assisted machining (TAM) is considered one of the most effective approaches for improving the machinability of difficult-to-machine materials by intentionally modifying their physical and mechanical properties through controlled heating. The primary objective of TAM is to reduce material strength in the cutting zone, thereby lowering cutting resistance and improving machining efficiency [1], [2], [4]. Difficult-to-machine materials, such as titanium alloys, nickel-based superalloys, and high-strength steels, typically exhibit high cutting forces, severe tool wear, and poor surface integrity during conventional machining. These issues are mainly caused by their high strength, low thermal conductivity, and work-hardening behavior. The introduction of thermal energy into the cutting zone significantly improves these conditions by enhancing material plasticity and reducing hardness [1], [2], [6].

Among various TAM techniques, laser-assisted machining is one of the most widely studied and applied methods. In this process, a focused laser beam is directed to the region ahead of the cutting tool, providing localized preheating of the material before it is removed by the cutting tool. This approach minimizes unnecessary heating of the entire workpiece and reduces thermal distortion [8], [10].

As discussed in [8], the configuration of a laser-assisted machining system includes a laser source, a cutting tool, and a workpiece arranged in a manner that enables effective preheating. Figure 1 illustrates the schematic representation of the laser-assisted machining process, where the laser beam is applied ahead of the cutting zone to reduce material strength before cutting, thereby improving cutting conditions and reducing tool wear [1], [2], [8].

Figure 1 — Schematic of laser-assisted machining process

Experimental studies have shown that the application of laser heating can reduce cutting forces by up to 30–50% and significantly extend tool life. Additionally, improved surface finish is achieved due to more stable cutting conditions [5], [8], [10]. Another important TAM technique is induction-assisted machining, where the workpiece is heated by electromagnetic induction. Unlike laser heating, induction heating provides a more uniform temperature distribution, which is particularly beneficial for machining large components. Studies have demonstrated that this method improves process stability and reduces vibration during machining [2], [6], [11].

Hybrid machining methods that combine thermal and ultrasonic assistance represent an advanced development in TAM technologies. In such processes, ultrasonic vibrations reduce friction between the tool and the workpiece, while thermal energy lowers material strength. This combined effect leads to improved surface quality and reduced cutting forces [2], [7].

Temperature also plays a crucial role in determining surface quality. It has been reported that an increase in temperature leads to a reduction in surface roughness due to improved plastic deformation behavior of the material [3], [5], [9].

Based on experimental data reported in [3] and [5], Figure 2 shows the relationship between surface roughness and temperature, demonstrating a decrease in roughness with increasing temperature, which confirms the effectiveness of TAM in improving surface finish [3], [5], [9].

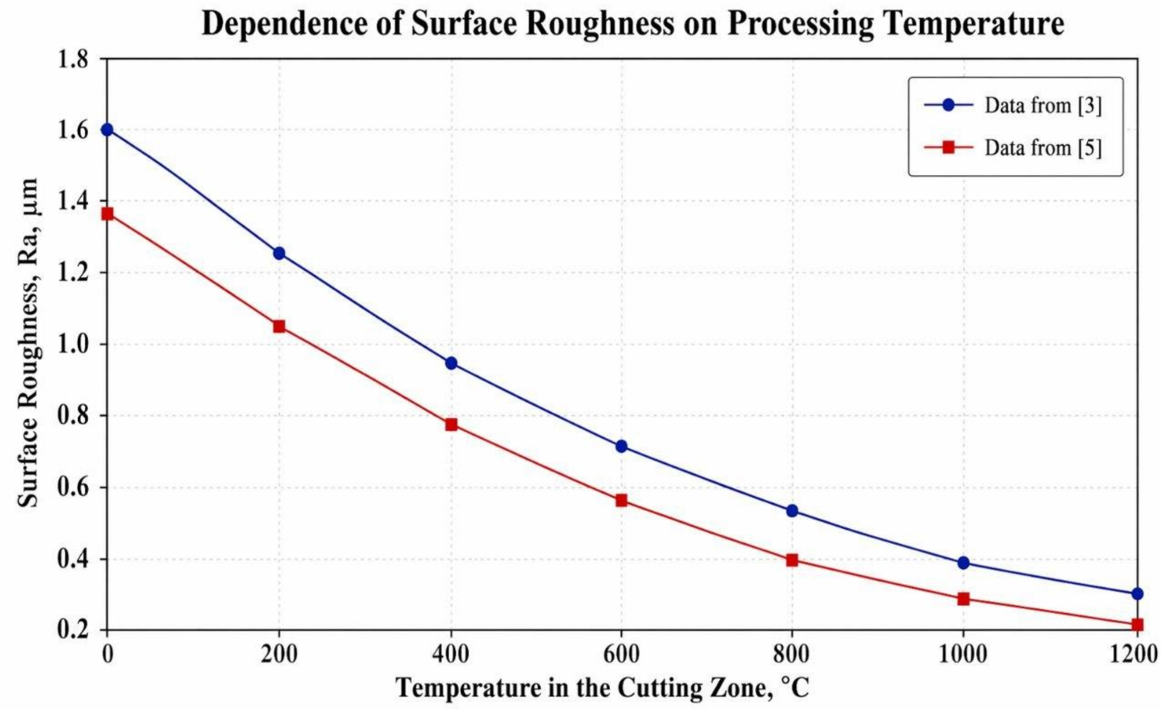

Figure 2 — Relationship between surface roughness and temperature

Furthermore, numerical and experimental studies indicate that there exists an optimal temperature range that maximizes machining performance. Exceeding this range may result in undesirable metallurgical changes, such as phase transformations or thermal damage to the material [2], [11]. Overall, the analysis of thermally assisted machining methods demonstrates that TAM significantly enhances machining performance, reduces tool wear, and improves surface quality. However, the effectiveness of each method depends on proper selection of process parameters, especially temperature, cutting speed, and feed rate [1], [2], [3].

Comparative Analysis of Thermally Assisted Machining Methods. Thermally assisted machining (TAM) comprises several technological approaches, each characterized by specific heat generation mechanisms, advantages, limitations, and application areas. The effectiveness of each method depends on the material properties, machining conditions, and required surface quality [1], [2], [8]. Laser-assisted machining (LAM) is one of the most precise and controllable TAM techniques due to its ability to provide localized heating directly in the cutting zone. As reported in [1] and [8], this method significantly reduces cutting forces and tool wear by softening the material ahead of the cutting tool. However, its industrial implementation is often limited by high equipment costs and the need for precise control of laser parameters [8], [10].

In contrast, induction-assisted machining offers a more uniform temperature distribution within the workpiece. This makes it particularly suitable for machining large components where homogeneous heating is required. Studies have shown that induction heating improves process stability and reduces vibration, although it lacks the localized heating capability of laser-based methods [2], [6].

Hybrid machining methods, which combine thermal assistance with ultrasonic vibrations, represent a promising direction in advanced manufacturing. According to [2] and [7], these methods provide enhanced performance by simultaneously reducing friction and material strength. As a result, improved surface quality and reduced tool wear can be achieved. Despite these advantages, the complexity and cost of such systems remain challenges for widespread industrial adoption [7].

A comparative analysis of TAM methods indicates that all approaches aim to reduce cutting resistance by modifying material properties through controlled heating. However, their effectiveness varies depending on process parameters such as temperature, cutting speed, and feed rate [1], [3], [11].

Table 1 — Comparative analysis of thermally assisted machining methods

Method	Heat Source	Advantages	Limitations	Applications
Laser-assisted	Laser beam	High precision, localized heating	High cost	Titanium alloys, superalloys
Induction-assisted	Electromagnetic field	Uniform heating	Low localization	Large components
Hybrid (Thermal + Ultrasonic)	Heat + vibration	Reduced friction, high stability	Complex system	Precision machining

The comparative evaluation reveals that laser-assisted machining is наиболее suitable for applications requiring high precision and localized heating, while induction-assisted methods are better suited for large-scale components. Hybrid techniques demonstrate the highest performance potential due to their combined effects, although their implementation requires further technological development [2], [7], [8].

Temperature plays a critical role in all TAM processes. As reported in [3], [5], and [9], increasing temperature generally leads to reduced cutting forces and improved surface finish. However, exceeding the optimal temperature range may cause thermal damage or degradation of material properties [3], [5], [11].

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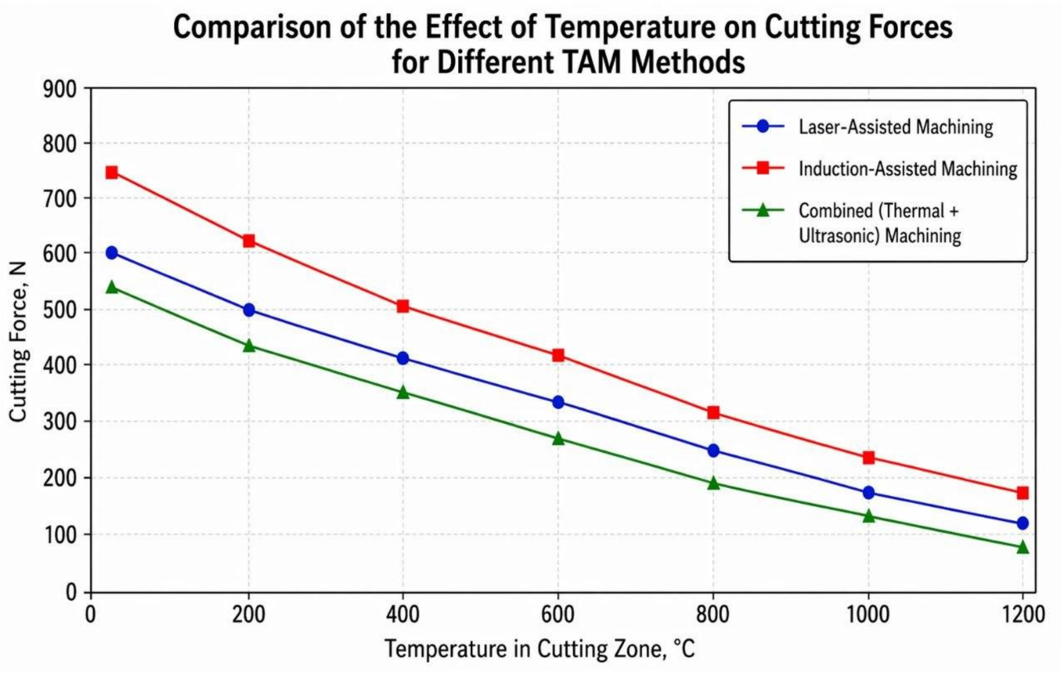

Figure 3 — Comparison of cutting force versus temperature for different TAM methods

Thus, the selection of an appropriate TAM method should be based on a comprehensive evaluation of material characteristics, machining requirements, and economic factors. Among the available techniques, hybrid methods are considered the most promising for future applications due to their superior performance and potential for process optimization [2], [7].

Conclusion. This paper presents a comprehensive review of thermally assisted machining (TAM) methods applied to difficult-to-machine materials. Based on the analysis of recent studies, it has been established that the application of controlled thermal energy significantly enhances machining performance by reducing material strength in the cutting zone, thereby lowering cutting forces and improving tool life [1], [2], [4]. The review highlights that various TAM techniques, including laser-assisted, induction-assisted, and hybrid machining methods, contribute to improved surface quality, reduced tool wear, and enhanced process stability. Each method exhibits distinct advantages and limitations, which must be carefully considered depending on the machining conditions and material characteristics [5], [7], [9].

Comparative analysis indicates that laser-assisted machining offers high precision and localized heating, induction-assisted methods provide uniform temperature distribution, and hybrid techniques deliver superior performance due to the combined effects of thermal and mechanical assistance [2], [6], [8]. It is also demonstrated that temperature is a critical parameter influencing machining outcomes. An increase in temperature generally leads to reduced cutting forces and improved surface finish; however, exceeding the optimal temperature range may result in adverse metallurgical changes and degradation of material properties [3], [5], [11].

In conclusion, thermally assisted machining represents a promising and effective approach for improving the machinability of advanced materials. Its application can lead to increased productivity, reduced manufacturing costs, and enhanced product quality. Future research should focus on the development of hybrid technologies and optimization of process parameters through advanced modeling and experimental validation [2], [7], [11].

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