Optimization of Cutting Parameters During Sustainable Machining of Alloy X-750 With Coated Carbide Tool Using RSM and AI: A Review

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Abstract: The exceptional mechanical characteristics and resistance to wear and corrosion of superalloys, such as Alloy X-750, present considerable problems for their sustainable machining and can result in increased energy consumption and accelerated tool wear. Studying response surface methodology (RSM) and artificial intelligence (AI) methodologies from the literature, this research looks into optimizing cutting parameters in machining Alloy X-750 deploying coated carbide tools. By determining the ideal machining parameters that reduce tool wear and power consumption while guaranteeing high-quality surface finishes, this review aims to study the factors responsible for improving machining efficiency, tool life, and environmental sustainability. The article analyzes previous studies to identify research gaps and limitations in the field. The study investigates how different cutting parameters, such as feed rate, depth of cut, and cutting speed, affect the machining process results. It is observed from the literature that building the mathematical model that predicts the desired answers can be aided by using RSM in the experiment design and parameter interaction analysis. More significantly, AI and machine learning algorithms can be used in tandem to analyze experimental data, draw conclusions from the machining process, and forecast ideal cutting conditions outside of the experimental setup. Results from the literature highlight the future potential of RSM and AI to encourage sustainable machining processes. Specifically, according to the literature, optimized cutting parameters can reduce tool wear by up to 30% and power usage by 25%. This study broadens the subject's understanding of superalloy machining and offers practical suggestions to industry professionals for implementing sustainable production techniques.
Keywords: *Optimization of Cutting Parameters, Alloy X-750, Coated Carbide Tools, Response Surface Methodology, Sustainable Machining, Artificial Intelligence.*

1. Introduction

Sustainable machining techniques are necessary to maintain efficient manufacturing operations and lessen environmental impact. Even though "Alloy X-750" is widely renowned for its durability in high-temperature applications, its challenging cutting properties present unique machining issues (Chetan et al., 2015; Gajrani et al., 2022). Sustainable machining technologies are becoming increasingly important for modern businesses due to growing environmental concerns and the pressing demand for production efficiency (Raabe, 2023; Thakur & Gangopadhyay, 2016). Ni-based alloys have desirable properties, but machining them offers significant challenges, including rapid tool wear and difficult cutting conditions, due to their hardness and work-hardening tendencies (Thellaputta et al., 2017). Tools with coated carbide coatings have addressed some of these problems; they perform better, last longer, and resist wear better than uncoated tools (Bhise & Jogi, 2023; Q. Wang et al., 2021).

By lowering friction and thermal deformation and consuming less energy and material waste, the coatings (usually made of materials like "titanium nitride (TiN), aluminum oxide (Al_2O_3), and titanium carbonitride (TiCN)") improve the sustainability of machining operations (Schalk et al., 2022). In a time dominated by technological breakthroughs, the hunt for materials that can withstand high temperatures, challenging working conditions, and corrosive chemical environments has intensified. The capacity to produce components with the highest "rupture strength, creep resistance, corrosion resilience, and oxidation resistance" is a well-known feature of nickel (Ni) superalloys (Bohat & Sharma, 2023c; Gupta et al., 2019). Superalloys like those composed of nickel are widely used in heavy-duty machinery, turbine components, nuclear reactors, and aircraft engines because of their consistent yield strength, enhanced fatigue life at high pressures, and thermal resistance at extremely high temperatures (Liu et al., 2018).

The face-centred cubic structure of these alloys allows them to maintain ductility at extremely low temperatures, making them useful in space rocket bodies, cryogenic tanks, and superconducting materials. One of the Ni-based superalloys frequently used for high-temperature applications is "Inconel X-750" (Bohat & Sharma, 2023c; Gupta et al., 2019). Because of their resistance to oxidation, carburization, and high temperatures, Inconel alloys are perfect for high-temperature devices and help prevent cracks from chloride stress corrosion (Gupta & Sood, 2017). The high "chemical affinity, low heat transfer, and high hot hardness" of Inconel alloys make cutting difficult. This leads to increased tool power consumption, wear on the tools, problems with surface quality, and carbon emissions (Pusavec et al., 2010, 2015).

Plastic deformation converts the energy released during cutting into heat, which affects the freshly formed surface and hastens tool wear (Kitagawa et al., 1997). Because of EPA (Environmental Protection Agency) regulations and growing expenses, industries are reducing energy use. They are concentrating on tool wear and machining pressures that provide cooling technologies and applications to reduce energy consumption (Gupta et al., 2020, 2021; Khan et al., 2020). By influencing other machining parameters, including "tool wear, surface quality, and machining temperature," different cooling strategies also result in effective machining characteristics (Bohat & Sharma, 2023c; Ross et al., 2020). Using various cutting parameters during dry machining, Devillez et al. looked at tool wear for Ni-based superalloys (Devillez et al., 2007). Zhang et al. (2012) machined Ni super alloys using MQL and dry-cutting circumstances to evaluate the tool's life and the surface finish of the workpiece (Zhang et al., 2012).

From the published research, it was found that machining and optimization have been heavily researched fields (Bohat & Sharma, 2022, 2023b, 2023c, 2023a; Kumar et al., 2022; Lal et al., 2024; Rohilla et al., 2021; Sharma et al., 2023, 2019, 2020; G. Singh et al., 2020). However, less research has been done on the sustainable machining of X-750 Nickel alloy with carbide inserts and using RSM and AI to optimize cutting parameters. Research on the efficiency of RSM and AI in machining Alloy X-750 with coated carbide tools is limited, and the connection between tool performance and sustainable parameters has not been explored well. However, recent studies demonstrate that RSM and AI may improve machining parameters for materials (Şirin et al., 2021; Y. Zhao et al., 2023).

2. Research Questions and Objectives

2.1 Research Questions

The following are the study's research questions:

- What are the various roles of the RSM and AI in optimizing cutting parameters?
- How do coated carbide tools improve the X-750 alloy's machining performance?
- How do the optimized cutting parameters impact the machining operation's tool life, sustainability, and effectiveness?

2.2 Objectives

The following are the research's objectives:

- To study the purpose of AI and RSM in machining alloy X-750 through optimizing cutting parameters.
- To study the effect of coated carbide tools on the machining performance of alloy X-750.
- To study the effect of optimized cutting parameters on the machining operation's tool life, sustainability, and effectiveness.

3. Literature Review

3.1 Sustainable Machining

The cutting-based technique, called "sustainable machining," generates economically viable and secure work while preserving energy and natural resources (Dornfeld, 2014; Gajrani et al., 2022). This enhances the reputation of companies and aids in regulatory compliance (Ghandehariun et al., 2015; Haleem et al., 2023). Sustainable machining addresses environmental issues associated with traditional production methods while "minimizing waste, energy, and resource usage." Economic efficiency is increased when the "cost of materials, energy, and waste disposal" is reduced (Hegab et al., 2018; Jayawardane et al., 2023; Korkmaz et al., 2023).

3.2 Machinability Issues with Superalloys Like Alloy X-750

Superalloys are recognized for their exceptional strength, resistance to oxidation and corrosion, and capacity to maintain their mechanical qualities at elevated temperatures. One example of such an alloy is "alloy X-750". However, superalloys' advantageous properties for crucial applications in the "nuclear, aerospace, and chemical sectors" also present complex machining problems (Mali & Unune, 2017; Vetri Velmurugan et al., 2019). Superalloys like "alloy X-750" cause tool wear, affecting the components' output and quality. "Longer-lasting machinery, slower cutting rates, and more frequent tool changes" are the outcomes of superalloy machining, which uses more energy than machining regular materials. Specific cooling methods and lubricants are needed to preserve component integrity and tool life since the heat produced during superalloy machining can be harmful to the workpiece and tool (Tasbasi et al., 2020; Venkatesan, 2022; R. Wang et al., 2022). Superalloy X-750 is machined using "coated carbides, PCD, and CBN" to reduce energy consumption and tool wear. Cryogenic cooling systems and monitoring are employed to prolong tool life and lessen the impacts of heat. These solutions support sustainability and employ cutting-edge technologies to accomplish sustainability goals by solving specific industrial challenges (Arsecularatne et al., 2006; Chetan et al., 2015; Mia et al., 2022; Pawanr & Gupta, 2024; Qian et al., 2024; M. P. Singh et al., 2024).

3.3 Alloy X-750 and Its Machinability

Aluminum and titanium are added to the alloy X-750 to make it precipitation-hardable, and it has tensile solid and creep-rupture capabilities and good oxidation and corrosion resistance up to 700°C (Marsh & Kaoumi, 2016). The weight % composition range for X-750 is typical as: "70% nickel minimum, 14.0-5.0-9.0% iron, 2.25-2.75% titanium, 0.4-1.0% aluminum, 17.0% chromium, 1.0% manganese maximum, 0.7-1.2% niobium plus tantalum, 0.5% silicon maximum, .01% sulphur maximum, 0.08% carbon maximum, 0.5% copper maximum, and 1.0% cobalt maximum" (Marsh, 2018). Alloy X-750, a nickel-chromium alloy, is known for its high strength, corrosion resistance, and extreme temperature withstandability, making it ideal for aerospace, nuclear, and chemical processing industries. However, its machinability poses challenges, including rapid tool wear and complex material removal processes. (Varalakshmi et al., 2020). A few characteristics that impact machinability are high strength and toughness, work hardening, and thermal characteristics.

Because of Alloy X-750's extreme strength and toughness, particularly at high temperatures, more force is needed during machining, increasing tool wear and risk of tool breakage. Reduced tool life results from the material's abrasiveness and resistance to deformation. Due to its propensity to work harden, alloy X-750 becomes more resilient to wear as it experiences deformation. Work hardening happens quickly during machining, making future cuts much more challenging and requiring complex, sharp tools. Because of the alloy's high thermal resistance, the heat produced during machining is brutal to dissipate, which raises temperatures at the tool-workpiece contact. This may accelerate wear and deteriorate the material qualities of the cutting tool (Chauhan et al., 2024; Şirin et al., 2021; Varalakshmi et al., 2020; Vetri Velmurugan et al., 2019).

3.4 Studies on Machining Parameters and Tool Materials

Manufacturers of cutting tools and coatings must be highly productive because a 30% or 50% drop in tool price only decreases manufacturing costs by 1% (Mehra et al., 2013). The manufacturing industry extends the life of tools by utilizing TRD, PVD, CVD, etc (Ertürk & Kayabaşi, 2019; Thakur et al., 2014). Coated tools are commonly used in realistic finishing operations with low feeds and cut depths (Liew et al., 2004; Lungu, 2020; Outeiro et al., 2006). In comparison to uncoated tools, cutting tools with hard coatings have longer service lives, less tool damage, and better performance, economy, and productivity during machining (Lungu, 2020; Paul et al., 2015; Thepperumal et al., 2021). The best coating choice for machine tools is determined by how well it reduces adhesion, abrasion, and tribo-oxidation wear. “Physical Vapor Deposition,” or PVD, techniques create multilayer coatings, freestanding structures, and deposits of graded composition. It also increases performance, adhesion, roughness, and strength and is compatible with hard coatings. Tool life is increased by 7.5 times with PVD methods (Butt et al., 2021; Dabees et al., 2022; Grzesik, 2008; Kiran & Nagaraju, 2020; Kümmel et al., 2013; Mohanty et al., 2015; Suresh et al., 2012; Varghese, 2019; Zlamal et al., 2019).

While reactive deposition outperforms magnetron sputtering in terms of efficiency, enabling the formation of lower-pressure plasma and higher ionization effectiveness, cathodic arc deposition creates thin layers on surfaces (Cordes, 2012; Michna et al., 2021). Using LARC and CERC technologies, triple coatings provide improved resistance to wear, corrosion, and oxidation, as well as longer tool life and consistency for high-performance cutting instruments (Ben Hassine et al., 2021; Cselle et al., 2009; Hao et al., 2019; Strnad & Buhagiar, 2010). TiAlN coatings are becoming increasingly common in the metal-cutting industry because they increase productivity and prolong tool life. These are distinguished by their chemical stability and resistance to oxidation wear (Ben Hassine et al., 2021; Chowdhury et al., 2021; Kotsilkova et al., 2019; Ren et al., 2018). The machining of “alloy X-750” necessitates careful consideration of various aspects, including “cutting speed, feed rate, tool shape, and cooling” procedures. For best results and “heat reduction, modern tool materials, coatings, and proper cooling” are required (Chinchanikar & Choudhury, 2013; Kaçal, 2020; Korkmaz et al., 2023; Senthil Kumar et al., 2006; Şirin et al., 2021; Sulaiman et al., 2019).

3.5 Coated Carbide Tools

Coated carbide tools have made machining hard-to-cut materials such as hardened steels, titanium alloys, nickel alloys, and superalloys easier. These superior features are characterized by reduced friction, wear prevention, and heat resistance that altogether increase the life span of these tools and improve their performance at high temperatures. Furthermore, coatings improve the interaction between the tool and workpiece, making cuts more predictable and enhancing the overall quality of the machined part (Bouzakis et al., 2014; Sharma & Gupta, 2019). High temperature-resistant coatings cover the tool’s cutting edge during high-heat machining processes. This is essential because superalloys like alloy X-750 must tolerate high temperatures when machining (Şirin et al., 2021). Alloy X-750 is widely machined with carbide tools coated with aluminum oxide (Al_2O_3), titanium oxide (TiN), titanium carbonitride (TiCN) and titanium aluminum nitride (TiAlN). Coatings like this significantly favour conditions for high-heat machining because they “increase wear resistance, perform well at high temperatures, enhance tool life” (Kannan & Kannan, 2018; Serro et al., 2009; Thakur & Gangopadhyay, 2016).

3.6 Optimization Techniques in Machining

Advanced coating methods are becoming more complex to find the best operational parameters with increasing production capacity (Heinrichs et al., 2021; Inspektor & Salvador, 2014; Jurko et al., 2012; J. Zhao et al., 2022).

3.6.1 Response Surface Methodology (RSM)

Optimizing cutting parameters for a range of materials, including superalloys that are difficult to machine, is possible with RSM, a statistical and mathematical machining technique. This process comprises four steps: “formulating coefficients, designing test plans, performing a lack-of-fit test, and testing certain regions.” When multiple variables are impacting the response variable, RSM is crucial. (Lamidi et al., 2023; Öktem et al., 2005; Palanikumar & Palanikumar, 2021; Sarabia & Ortiz, 2009; Seikh et al., 2019). The three main objectives of RSM in machining processes are to maximize “material removal rates, limit tool wear, and reduce surface roughness.” It effectively finds the best combination of machining settings for superalloys like “Alloy X-750 and Inconel 718.” RSM reduces the need for trial runs and saves time and resources by understanding the relationships between machining parameters and demonstrating how they affect the overall machining outcome (Atif et al., 2024; Gangil & Pradhan, 2017).

3.6.2 Artificial Intelligence (AI)

Researchers Lantek (2022) and Soulpageit (2021) have examined the application of artificial intelligence in the sheet metal cutting industry for several reasons, including “automation, defect discovery, and cost management." Machine learning techniques significantly improve machining operations' optimization, including "genetic algorithms, support vector machines (SVM), and neural networks." They can recognize trends, predict results, and instantly adjust cutting parameters. AI models can accurately simulate complex interconnections, especially in superalloy machining. Their accuracy may increase as AI models advance and adjust to shifting machining conditions. When AI models have sufficient processing capacity, they may modify machining parameters in real time to increase output and quality (Deaconescu & Deaconescu, 2021; Plathottam et al., 2023; Ullrich et al., 2024).

3.7 Research Gaps

Concerns regarding the environmental impact of "alloy X-750" machining are raised by the paucity of research on the efficacy of RSM and AI in cutting parameter optimization. The literature usually focuses on a few critical parameters, ignoring other crucial factors like cooling conditions and tool path. The most optimal cutting conditions are still unpredictable to AI, and research on sustainable machining often omits important sustainability criteria like "life cycle analysis and energy use." More research is needed to properly understand the long-term effects of enhanced cutting parameters and sustainability.

4. Discussions

The primary goal of this review article is to assess past research on "Inconel alloy X-750" sustainable machining. It is imperative to consider optimizing several aspects such as "cost reduction, rework cycle frequency, tool cutting, reduction of hazardous gas generation, recycling, productivity enhancement, waste minimization," and identification of optimal machining conditions. The literature review emphasizes the necessity of figuring out the best parameters for tool turning performance, the necessity of reducing the amount of cutting fluid used because of environmental concerns, and the possibility of developing more efficient methods like coatings and carbide tools coated with titanium nitride. RSM's methodical approach makes it perfect for early study and parameter adjustment, but AI's superior modelling and flexibility make it shine in data-driven settings.

This review article explored the research on optimizing the cutting parameters for alloy X-750 using AI and RSM. It is observed through the literature that RSM cable is enough to improve relationships between various cutting variables, while AI can aid in forecasting and manipulating parameters. The review article seeks to pinpoint the aspects that affect "machining performance, tool longevity, productivity, and sustainability." The effective use of AI and RSM assists in achieving optimization that is correct, quick, and adaptable; moreover, it aims to improve the "sustainability, tool life, and efficiency of X-750". Their function of reducing energy consumption and minimizing material wastage helps establish eco-conscious behaviours such as reducing "electricity consumption and extending tool life." The tools enhance the machining capabilities of "alloy X-750" due to the coated carbide composition that ensures durability to exceed wear resistance.

The instruments improve smoothness, durability, and abrasion. They accelerate cutting without affecting product quality or tool structure. RSM and advanced techniques can maximize cutting parameters, tool longevity, sustainability, and manufacturing efficiency. This study analyzes how cutting parameters in machining operations are optimized for materials like "alloy X-750." Due to its endurance, strength, and hardness, the material must be protected from tool wear. Due to its thermomechanical properties and work hardening tendency, Alloy X-750 requires "feed rate, depth of cut, and cutting speed" adjustments. High temperatures and abrasive material cause considerable tool wear. Tools and cutting settings must balance wear reduction and machining efficiency to last. A protective coating and high-wear-resistant materials reduce tool wear on carbide tools. Cutting without vibration is limited by machine tool power and rigidity. These factors can help manufacturers design durable and cost-effective alloy X-750 machining procedures.

5. Conclusion

The study employs RSM, AI, and sophisticated techniques to optimize cutting parameters for long-term machining of "alloy X-750" using coated carbide tools. Heat, tool wear, and chip breakage are problems. RSM predicts and evaluates the link between cutting parameters and machining outcomes. Machine learning is critical for managing complicated connections and providing data-driven, customizable machining insights for long-term "alloy X-750" machining. AI's understanding of machining has increased, enabling more exact cutting parameter prediction and adjustment. AI can predict complicated nonlinear connections from large datasets. Moreover, AI methods have made changing monitoring and real-time machining settings easier by encouraging energy and waste reduction. This evaluation emphasizes that although RSM and AI provide useful tools and analysis for machining alloy X-750, their combination may increase the advantages of each technique. Technically, financially, and ecologically sustainable machining techniques can be optimized using a hybrid methodology that blends RSM with AI. "This approach combines data-driven, optimization, and dynamic prediction with structured experimental design and modelling" using this approach.

Future research should focus on substantial machining techniques, novel tool coatings, and combining RSM and AI in machining optimization. Utilizing these techniques on more difficult-to-machine materials can enhance manufacturing procedures and efficiency. Alloy X-750 can be machined sustainably and efficiently using coated carbide tools if cutting parameters are optimized using RSM and AI. Future studies should focus on integrating these optimization strategies with practical machining procedures. Rigorous optimization using RSM and AI is required for the sustainable machining of alloy X-750. However, given the complexity of the subject matter and the assumed quadratic relationship, the results might not be accurate. Applying AI technologies and powerful computing resources may also impact the viability of AI-driven optimization. To fully understand the economic and environmental implications of AI and RSM in machining operations, more research is needed to integrate human experience with computational optimization methodologies.

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