

**INVESTIGATION OF ULTRASONIC VIBRATION-ASSISTED
DRILLING METHODS IN DENTAL IMPLANT
PROCEDURES: A COMPARATIVE STUDY ON REDUCING
FORCE AND THERMAL EFFECTS**



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ÖZYEGİN UNIVERSITY

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PROCEDURES: A COMPARATIVE STUDY ON REDUCING
FORCE AND THERMAL EFFECTS**

**by
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To my beloved Shima and my loyal companion Roma



DECLARATION OF ORIGINALITY

I hereby declare that I am the sole author of this thesis and that this is the true copy of my thesis, including the final revisions, approved by my thesis committee. All data and information have been obtained, produced, and presented in accordance with the rules of research ethics and principles of academic honesty. As required by these rules, to the best of my knowledge I have acknowledged ideas, thoughts, and any copyrighted material in accordance with the standard referencing rules. I certify that any part of this thesis has not been submitted for a degree or diploma in another educational institution.

Deniz Mansouri

ABSTRACT

Dental implants are widely regarded as one of the most effective and reliable solutions for tooth replacement due to their ability to restore functionality and aesthetics while stimulating bone growth and preventing bone loss. However, the surgical drilling process required for implant placement presents significant challenges, especially in maintaining the structural integrity of the bone. Conventional Drilling (CD) methods, while effective, often result in high thrust forces, torque, and elevated temperatures. These mechanical and thermal stresses can cause adverse effects such as bone microdamage, thermal necrosis, prolonged healing times, and reduced implant stability, ultimately compromising the success of the procedure.

In recent years, Ultrasonic Assisted Drilling (UAD) has emerged as a promising alternative, offering potential advantages in reducing drilling forces and minimizing thermal effects. By introducing high-frequency vibrations into the drilling process, UAD reduces the continuous contact between the drill bit and the bone, resulting in lower thrust forces, improved cutting efficiency, and reduced heat generation. These characteristics suggest that UAD has the potential to address the limitations of CD while improving patient outcomes. Despite its advantages, the application of UAD in dental implantology remains underexplored, particularly regarding its impact on the unique mechanical and thermal behaviors of jawbone tissues.

This study aims to investigate and compare the mechanical and thermal behavior of both CD and UAD methods in dental drilling applications. A combination of Finite Element Method (FEM) simulations and experimental analyses was employed to evaluate critical parameters such as thrust force and temperature during drilling. The FEM simulations were designed to replicate realistic surgical scenarios by accounting for variables

such as rotational speed, drill bit geometry, bone material properties, and vibration parameters. Experimental data were used to validate the FEM results, ensuring accuracy and relevance to clinical practice.

The findings from this study offer valuable insights into the efficacy of UAD as a dental drilling technique, potentially guiding future practices and contributing to safer, more effective implant procedures. Results demonstrate that UAD reduces thrust forces by 30–35% compared to CD. Additionally, UAD minimizes thermal effects, reducing maximum drilling temperatures by 25–30%. These reductions are crucial for preserving bone integrity, contributing to improved osseointegration and reduced healing time. The lower thermal and mechanical stresses observed in UAD contribute to enhanced osseointegration—the process by which bone tissue integrates with the implant—leading to an expected reduction in recovery times and improved long-term stability of dental implants.

It is hypothesized that UAD will produce reduced drilling force and lower thermal stresses compared to CD, facilitating less traumatic and more controlled bone removal. This research provides a comprehensive evaluation of UAD's mechanical and thermal effects in dental applications, addressing a critical gap in the literature. A Response Surface Methodology (RSM) was employed to perform a sensitivity analysis and multi-objective optimization. The study contributes to the optimization of UAD parameters, such as vibration frequency and amplitude, tailored specifically for dental implantology. The analysis identified an optimal parameter set comprising a rotational speed of 5499 rpm, vibration frequency of 34.50 kHz, and amplitude of 13.07 μm . By combining experimental data with simulation insights, this work offers valuable guidelines for adopting UAD in clinical practice, paving the way for safer, more efficient, and patient-centered surgical procedures.

Keywords: Conventional Drilling; Ultrasonic Assisted Drilling; Response Surface Method.

ÖZET

Diş implantları, işlevselliği ve estetiği geri kazandırma yeteneklerinin yanı sıra kemik büyümesini teşvik etme ve kemik kaybını önleme özellikleri sayesinde, diş kaybının tedavisinde en etkili ve güvenilir yöntemlerden biri olarak kabul edilmektedir. Bununla birlikte, implant yerleştirilmesi için gerekli olan cerrahi delme işlemi, özellikle kemiğin yapısal bütünlüğünü koruma açısından önemli zorluklar sunmaktadır. Geleneksel Delme (CD) yöntemleri etkili olmakla birlikte, genellikle yüksek itme kuvvetleri, tork ve artan sıcaklıklar gibi olumsuz sonuçlara yol açmaktadır. Bu mekanik ve termal gerilmeler, kemik mikro hasarları, termal nekroz, uzun iyileşme süreleri ve implant stabilitesinin azalması gibi olumsuz etkilere neden olarak, işlemin başarısını riske atmaktadır.

Son yıllarda, Ultrasonik Destekli Delme (UAD), delme kuvvetlerini azaltma ve termal etkileri en aza indirme konularında önemli avantajlar sunan umut verici bir alternatif olarak ortaya çıkmıştır. UAD, delme işlemine yüksek frekanslı titreşimler ekleyerek matkap ucu ile kemik arasındaki sürekli teması azaltır; bu sayede daha düşük itme kuvvetleri, geliştirilmiş kesme verimliliği ve daha az ısı üretimi sağlanır. Bu özellikler, UAD'nin CD'nin sınırlamalarını giderme ve hasta sonuçlarını iyileştirme potansiyeline sahip olduğunu göstermektedir. Ancak, UAD'nin diş implantolojisindeki uygulaması, özellikle çene kemiği dokularının benzersiz mekanik ve termal davranışları üzerindeki etkileri açısından yeterince araştırılmamıştır.

Bu çalışma, diş delme uygulamalarında CD ve UAD yöntemlerinin mekanik ve termal davranışlarını araştırmayı ve karşılaştırmayı amaçlamaktadır. Delme sırasında itme kuvveti, tork ve sıcaklık gibi kritik parametreleri değerlendirmek için Sonlu Elemanlar Yöntemi (FEM) simülasyonları ve deneysel analizlerin bir kombinasyonu kullanılmıştır. FEM simülasyonları, döner hız, matkap ucu geometrisi, kemik malzeme özellikleri ve titreşim parametreleri gibi değişkenleri dikkate alarak gerçekçi cerrahi senaryoları yeniden

oluşturacak şekilde tasarlanmıştır. Deneysel veriler, FEM sonuçlarının doğruluğunu ve klinik uygulamalarla olan ilişkisini sağlamak amacıyla kullanılmıştır.

Bu çalışmadan elde edilen bulguların, UAD'nin bir diş delme tekniği olarak etkinliği hakkında değerli bilgiler sunması ve gelecekteki uygulamalara rehberlik ederek daha güvenli ve etkili implant prosedürlerine katkı sağlaması beklenmektedir. Sonuçlar, UAD'nin delme sırasında itme kuvvetlerini azalttığını ve termal etkileri en aza indirdiğini, böylece kemik bütünlüğünü koruduğunu ve mikro çatlaklar ile termal hasar gibi komplikasyon riskini azalttığını göstermektedir. Bu iyileştirmelerin, kemik dokusunun implantla bütünleşmesini ifade eden osseointegrasyonu artırarak daha hızlı iyileşme sürelerine ve dental implantların uzun vadeli stabilitesine katkıda bulunması beklenmektedir.

Hipoteze göre, UAD'nin, CD kıyasla daha düşük delme kuvveti ve daha düşük termal gerilmeler üreteceği ve böylece daha az travmatik ve daha kontrollü bir kemik uzaklaştırma süreci sağlayacağı hipotez edilmiştir. Bu çalışma, literatürdeki önemli bir boşluğu doldurarak UAD'nin dental uygulamalardaki mekanik ve termal etkilerine yönelik kapsamlı bir değerlendirme sunmaktadır. Yanıt Yüzeyi Yöntemi (RSM) kullanılarak bir duyarlılık analizi ve çok amaçlı optimizasyon gerçekleştirilmiştir. Çalışma, özellikle dental implantolojiye özgü titreşim frekansı ve genlik gibi UAD parametrelerinin optimizasyonuna katkı sağlamaktadır. Analiz sonucunda, 5499 devir/dakika dönme hızı, 34.50 kHz titreşim frekansı ve 13.07 µm genlikten oluşan optimal bir parametre seti belirlenmiştir. Deneysel veriler ile simülasyon bulgularının birleştirilmesi sayesinde bu çalışma, klinik uygulamalarda UAD'nin benimsenmesi için değerli kılavuzlar sunmakta ve daha güvenli, daha verimli ve hasta odaklı cerrahi işlemler için bir yol açmaktadır.

Anahtar Kelimeler: Geleneksel Delme; Ultrasonik Destekli Delme; Yanıt Yüzeyi Yöntemi.

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LIST OF ACRONYMS AND ABBREVIATIONS

CD	Conventional Drilling
UAD	Ultrasonic Assisted Drilling
FEM	Finite Element Method
VAD	Vibration Assisted Drilling
FEA	Finite Element Analysis
MRR	Material Removal Rate
CFRP	Carbon Fiber-Reinforced Polymer
RPM	Revolutions Per Minute
HAZ	Heat-Affected Zone
DOF	Degree of Freedom
JC	Johnson-Cook
SPI	Serial Peripheral Interface
DC	Direct current
RMSE	Root Mean Square Error
MAE	Mean Absolute Error
MAPE	Mean Absolute Percentage Error
sMAPE	Symmetric Mean Absolute Percentage Error
MD	Maximum Difference
RSM	Response Surface Methodology
RMS	Root Mean Square

1. INTRODUCTION

1.1 Literature Review

In this chapter, the literature on key topics relevant to advanced drilling techniques and their applications is reviewed comprehensively. The discussion begins with an overview of bone drilling in Section 1.1.1, which establishes the fundamental principles and challenges associated with drilling in medical contexts, such as orthopedic and dental surgeries. This section provides a detailed examination of bone drilling techniques, highlighting issues such as thrust force, heat generation, and structural integrity, while emphasizing its critical role in implant placement and bone stabilization.

Building on this foundation, Section 1.1.2 explores vibration-assisted drilling Vibration Assisted Drilling (VAD), an innovative approach that integrates controlled vibrations into the drilling process. The literature in this section highlights how VAD enhances cutting efficiency by reducing mechanical stresses and improving thermal management. These benefits make it particularly effective for both biological applications, such as surgical procedures, and industrial applications involving advanced materials.

The progression continues with UAD in Section 1.1.3, which expands on the principles of VAD by employing high-frequency vibrations to improve machining performance. The review delves into UAD's application in demanding industries such as aerospace and automotive, emphasizing its advantages in reducing cutting forces, facilitating chip fragmentation, and achieving superior surface finishes. This section illustrates how UAD addresses challenges associated with hard-to-machine materials and components requiring high precision.

Section 1.1.4 presents experimental studies on UAD, offering empirical evidence of its effectiveness across a wide range of materials. These studies highlight measurable

improvements in thrust force reduction, tool life extension, and surface quality. The findings also underscore UAD's versatility, demonstrating its applicability in diverse fields, from manufacturing to medical engineering.

Parametric studies on UAD are reviewed in Section 1.1.5, focusing on the influence of key parameters such as ultrasonic frequency, amplitude, drilling speed, and feed rate. This section examines how the systematic variation and analysis of these variables impact the efficiency and precision of UAD processes. By synthesizing results from various experimental setups, this section provides valuable insights into understanding the optimal configurations for different applications.

Finally, Section 1.1.6 reviews numerical studies on UAD, which utilize computational models to simulate and analyze drilling mechanics. These studies offer a theoretical perspective on the effects of ultrasonic vibrations, providing predictions for cutting forces, thermal behavior, and chip formation. By bridging experimental findings with numerical simulations, this section highlights the potential for further refinement of UAD techniques, ensuring their adaptability to both medical and industrial requirements.

1.1.1 Bone Drilling

Bone drilling is a critical procedure in both orthopedic and dental surgeries, extensively studied due to its essential role in therapeutic and diagnostic interventions. It facilitates internal fixation of fractures and placement of implants, such as screws, plates, and nails, which are crucial for structural stability and bone healing. Despite its significance, the bone drilling process introduces mechanical and thermal challenges that have been a focus of numerous studies aimed at optimizing clinical outcomes.

The mechanics of bone drilling are based on the axial cutting force and torque generated by a rotating drill bit to remove material from the bone surface. Similarly to machining processes, material removal occurs through a continuous interaction between

the cutting edge of the tool and the bone. In conventional surgical practices, this procedure is performed manually, relying on the skill and expertise of the surgeon, who applies axial cutting force to guide the drill bit through the bone surface. However, the literature highlights several complications associated with CD techniques.

Pandey and Panda [1] investigated the delamination of the bone surface layers and the formation of microcracks along the inner surface of drilled holes, both of which compromise the structural integrity of the bone-implant interface. Such defects increase the risk of implant instability and prolonged healing times. Furthermore, Kasiri et al. [2] emphasized that these issues are exacerbated by improper control of drilling parameters, particularly high thrust forces and torque, which can lead to catastrophic outcomes, including fractures in cortical bone.

Another significant mechanical challenge in bone drilling is the risk of drill bit breakage. Excessive forces or torque can cause the drill bit to become stuck during the procedure, increasing the probability of failure. Bassi et al. [3] documented techniques to mitigate these risks, noting that drill bit failure incidents disrupt surgical workflows and can result in complications, including damage to surrounding tissues. This underscores the importance of selecting appropriate drill geometries and materials to enhance reliability in clinical settings.

Thermal effects during bone drilling have also been extensively studied. The friction between the rotating drill bit and bone generates heat at the drilling site, converting mechanical energy into thermal energy. The poor thermal conductivity of bone, reported to range between 0.2 and 2.27 W/mK [4], exacerbates localized heat accumulation. Several studies have explored the consequences of elevated temperatures during drilling. Udiljak et al. [5] demonstrated that excessive heat generation could lead to thermal osteonecrosis, a condition characterized by the death of osteocytes (bone cells), reduced protein synthesis, and diminished regenerative capacity.

The critical temperature thresholds for thermal damage were established by Lundskog [6], who found that exposure to 50 ° C for 30 seconds resulted in thermal necrosis in rabbit bone. Eriksson and Albrektsson [7] further refined these findings, reporting that exposure to 47 ° C for 60 seconds produced similar histological damage in human bone. These studies emphasize the need to maintain drilling temperatures below these thresholds to preserve bone tissue viability and minimize complications during surgery.

The structural complexity of bone compounds the challenges of CD techniques. Cortical bone, characterized by its high stiffness and density, responds differently to mechanical forces compared to trabecular bone, which is porous and elastic. This heterogeneity necessitates precise control of the drilling parameters to minimize damage. For instance, Krause et al. [8] noted that excessive forces applied to cortical bone can cause fractures, while insufficient penetration in trabecular bone risks compromising implant stability.

To address these challenges, significant research has focused on alternative drilling methods. VAD has emerged as a promising approach, introducing high-frequency oscillations that reduce continuous contact between the drill bit and bone. Lopez et al.[9] demonstrated that VAD effectively lowers thrust forces and minimizes heat generation, leading to improved surgical outcomes. Similarly, osseodensification offers a novel technique that compacts bone tissue around the implant site, enhancing primary stability and promoting osteoblast activity, as reported by Bai et al. [10] and Brueckner et al. [11].

Enhanced cooling mechanisms have also been investigated to mitigate the thermal effects of drilling. Saline irrigation is widely used to dissipate heat at the drilling site. Bertollo et al. [12] reported that effective cooling could reduce peak temperatures by 20 to 30%, significantly improving cell viability. However, the effectiveness of cooling methods depends on various factors, including drilling speed, force, and bone density, as

highlighted by Francisquini et al. [13]. They concluded that optimizing cooling techniques significantly mitigates heat-induced damage during bone drilling procedures.

Despite these advancements, challenges remain in translating these innovations into routine clinical practice. VAD requires precise parameter control to avoid instability, while osseodensification depends on specific implant designs and geometries, limiting its versatility. In addition, the high cost of specialized equipment and the need for surgeon training pose barriers to widespread adoption. Future research should aim to further refine these methods, optimize their parameters, and evaluate their long-term clinical outcomes.

Thus, the literature demonstrates a comprehensive understanding of the mechanical and thermal challenges associated with bone drilling, as well as significant advancements in addressing these issues. However, gaps remain, particularly in the detailed exploration of advanced techniques and their adaptation for routine clinical applications. Further investigation in these areas is critical to enhancing the safety, precision, and effectiveness of bone drilling in both orthopedic and dental surgeries.

1.1.2 Vibration-Assisted Drilling

VAD is an innovative technique that has emerged as a promising alternative to CD methods, particularly in orthopedic and dental surgical applications. As discussed in Section 1.1.1, conventional methods often generate excessive thrust forces and temperatures, which lead to structural and thermal damage in bone tissue. VAD addresses these challenges by introducing controlled vibrations into the drilling process, offering significant advantages in minimizing mechanical and thermal stresses. By combining oscillatory motion with rotational force, VAD reduces continuous contact between the drill bit and bone tissue, thereby mitigating frictional heat and decreasing the forces required for material removal. This dual-action mechanism enables more efficient cutting while preserving the structural integrity and biological health of bone tissue [9, 14].

The key to VAD's effectiveness lies in its ability to reduce both mechanical and thermal stress during drilling. CD relies solely on continuous rotational motion to penetrate bone, often requiring high thrust forces and torques to cut through dense cortical layers. In contrast, VAD introduces oscillations—either ultrasonic or low-frequency—along the drill bit's axis, creating a pulsed cutting force. This pulsing reduces the amount of continuous energy applied to the bone surface, allowing for more efficient material removal with lower overall force. Studies have shown that VAD reduces thrust forces by up to 30% and peak temperatures by approximately 25% compared to conventional methods [9]. This reduction in mechanical and thermal load significantly decreases the likelihood of complications such as microdamage, delamination, and thermal osteonecrosis.

VAD's ability to adapt to the heterogeneous structure of bone further highlights its potential. Bone comprises a dense cortical layer, a porous trabecular layer, and, in some regions, an additional cortical layer. Traditional drilling often fails to account for the varying mechanical responses of these layers, leading to uneven force application, unintended damage, or incomplete penetration. By modulating force and vibration parameters, VAD ensures more consistent performance across different bone regions. For example, the oscillatory motion of VAD enhances cutting efficiency in dense cortical bone while maintaining precision and control in softer trabecular regions, reducing the risk of structural compromise [15, 16].

One of the most significant advantages of VAD is its ability to minimize the generation of heat at the drill-bone interface. As noted in previous studies, temperatures exceeding 47°C for 60 seconds can cause thermal necrosis, which compromises the bone's regenerative capacity and weakens the bone-implant interface. By reducing continuous friction through oscillatory motion, VAD lowers peak temperatures during drilling, preserving bone tissue viability and enhancing postoperative outcomes. Furthermore, VAD's

efficiency in reducing heat generation is particularly beneficial in procedures where cooling mechanisms are limited or impractical [17, 18].

In addition to reducing mechanical and thermal damage, VAD has demonstrated advantages in preserving the microarchitecture of bone near critical structures, such as nerves and blood vessels. Traditional drilling methods risk damaging these sensitive areas due to excessive thrust force and uncontrolled heat generation. VAD's precise control over force application and its ability to minimize heat significantly reduce the likelihood of such complications, thereby improving both the safety and effectiveness of surgical interventions. This capability is particularly advantageous in dental procedures, where proximity to neurovascular structures is a common concern [13, 19].

The integration of VAD with emerging techniques such as osseodensification further enhances its potential. Osseodensification transforms traditional subtractive drilling into a densification process, compacting bone tissue around the implant site rather than removing it. This method enhances primary stability by creating densified osteotomy walls that support the implant more effectively. Studies have shown that osseodensification, when combined with VAD, can further reduce mechanical stress during drilling while promoting osteoblast activity along the implant surface. This combination leads to faster and more reliable osseointegration, particularly in cases where bone quality is poor [11, 20].

In dental implantology, VAD has shown particular promise, as these procedures often involve drilling into a combination of cortical and trabecular bone in the jaw. CD in such scenarios poses risks of delayed healing, increased microfractures, and thermal necrosis. By precisely controlling thrust forces and vibration parameters, VAD minimizes these risks, ensuring better implant integration and long-term stability. Additionally, VAD reduces the likelihood of bone resorption, a common issue in dental implants where loss of bone density around the implant site can compromise its functionality over time [13, 19].

Another notable benefit of VAD is its ability to reduce drilling time without compromising precision or safety. The combined rotational and vibrational forces of VAD enhance cutting efficiency, resulting in shorter procedures. This reduction in drilling time not only lowers the risk of prolonged exposure to heat but also improves patient comfort and reduces the likelihood of postoperative complications. For surgeons, the enhanced efficiency translates into better workflow management, particularly in complex procedures requiring multiple drilling stages [9].

While VAD offers several advantages, certain challenges remain to be addressed. The technique requires precise optimization of parameters such as vibration frequency, amplitude, and thrust force to ensure consistent performance across various bone types. Improper parameter settings can lead to suboptimal cutting efficiency or instability during drilling. While these challenges are broadly applicable, they become particularly significant in dental implantology, where precise control of drilling forces and temperature is critical to prevent thermal damage and maintain the integrity of the bone-implant interface. Additionally, the adoption of VAD in clinical practice is often limited by the cost of equipment and the need for specialized training, especially in resource-limited settings. Further advancements are necessary to refine the technology, ensuring it becomes more accessible and user-friendly for widespread clinical adoption [14].

In dental implantology, bone drilling is a pivotal step that directly determines the success of implant placement and subsequent osseointegration. CD techniques are widely used; however, they frequently generate excessive thrust forces and elevated temperatures. Eriksson and Albrektsson [7] demonstrated that temperatures exceeding 47°C cause irreversible thermal necrosis in bone tissue. Such damage delays healing and reduces primary stability, both of which are essential for successful osseointegration.

Mechanical stresses further exacerbate the problem. Excessive thrust forces during CD can induce microcrack formation in cortical bone, weakening the structure around

the implant site [21]. Misir *et al.* [22] emphasized the importance of minimizing both drilling forces and thermal effects to preserve bone integrity and improve implant outcomes.

To address the limitations of CD, VAD and UAD have emerged as promising techniques. UAD introduces high-frequency vibrations along the drill axis, intermittently reducing the contact between the drill bit and bone. This oscillatory motion has demonstrated significant advantages over conventional methods. For instance, Aquilanti *et al.* [23] conducted an in vitro study on implant site preparation and reported that piezosurgical devices generated higher temperatures compared to rotatory drills. However, with sufficient cooling, these devices can be safely utilized while maintaining bone viability. Similarly, Maurer *et al.* [24] compared heat production during ultrasonic and conventional osteotomy. Their findings highlighted that ultrasonic devices required more time yet produced manageable thermal effects with adequate irrigation.

Despite these promising results, the application of UAD in dental implantology remains insufficiently explored. Existing studies often fail to account for the heterogeneity of jawbone, which comprises both cortical and trabecular bone, and its response to dynamic drilling forces. Additionally, while numerical simulations have predicted reductions in drilling forces and heat generation with UAD, experimental validations under clinically relevant conditions remain limited [25].

This study systematically investigates the mechanical and thermal effects of UAD in dental implant drilling. By combining experimental measurements with validated finite element simulations, the influence of UAD parameters—including vibration frequency, amplitude, and spindle speed—on thrust forces, temperature generation, and bone integrity is quantified. This research aims to bridge the existing gaps, providing insights for optimizing drilling conditions to ensure safer, more efficient, and clinically viable implant placement techniques.

1.1.3 Ultrasonic Vibration Assisted Drilling

UAD represents a significant advancement in drilling technology, combining high-frequency oscillations with rotational cutting to enhance precision and reduce mechanical and thermal stresses during drilling. While UAD has been extensively adopted in aerospace and automotive industries for machining advanced materials like titanium alloys and Carbon Fiber-Reinforced Polymer (CFRP), its underlying principles and benefits hold great potential for biomedical applications, including orthopedic and dental surgeries. In this context, UAD addresses key limitations of traditional drilling techniques and even standard VAD, offering unique advantages that align with the challenges of bone drilling.

The mechanics of UAD are central to its effectiveness. Unlike CD, which relies on continuous engagement between the drill bit and the material, UAD introduces ultrasonic vibrations—typically at frequencies above 20 kHz—superimposed on the drill bit’s primary rotational motion. This high-frequency oscillation creates a pulsed interaction at the cutting interface, reducing continuous contact time and significantly lowering thrust forces and frictional heat. Studies have demonstrated that UAD achieves a 25–35% reduction in thrust force and a similar decrease in heat generation compared to conventional methods, making it particularly effective for temperature-sensitive materials such as bone [26, 27]. By minimizing the thermal load, UAD reduces the risk of thermal necrosis in bone drilling, an outcome previously discussed as a critical concern in Section 1.1.1.

UAD also enhances chip removal efficiency, a persistent challenge in both industrial and medical drilling. In CD, continuous chip formation can lead to clogging, increased friction, and poor surface finishes. These issues are exacerbated in narrow or deep holes, such as those required in dental implantology or orthopedic screw placement. UAD’s oscillatory motion facilitates the fragmentation of chips into smaller pieces, allowing for efficient evacuation from the drilling site. This mechanism not only reduces

tool wear and prolongs operational life but also minimizes microdamage to surrounding tissues, critical for preserving the integrity of bone structures. Studies on CFRPs and titanium alloys highlight UAD's ability to prevent delamination and cracking in layered materials, and similar advantages could be directly applied to heterogeneous bone structures in medical contexts [28, 29].

The reduced mechanical load achieved with UAD is particularly advantageous in dense cortical bone, where CD often generates excessive forces that can lead to microcracks and delamination. As noted in Section 1.1.2, these structural defects compromise the bone-implant interface and prolong recovery times. By incorporating ultrasonic vibrations, UAD ensures more uniform stress distribution at the cutting site, reducing the likelihood of such complications. This precision is especially critical near sensitive anatomical structures, such as nerves and blood vessels, where uncontrolled forces or temperatures during drilling can result in severe complications [13, 19].

In addition to addressing mechanical and thermal challenges, UAD supports advanced techniques like osseodensification. Osseodensification, discussed in Section 1.1.2, transforms traditional subtractive drilling into a densification process, compacting bone tissue around the drill site. UAD's high-frequency oscillations enhance this process by ensuring controlled deformation of the osteotomy walls without generating excessive heat or stress. This combination has been shown to improve implant stability and accelerate osseointegration by promoting osteoblast activity along the implant surface, an outcome critical for dental and orthopedic implants [11, 20].

UAD's ability to operate with lower thrust forces and improved thermal management also enhances tool durability. In medical drilling, where precision is paramount, frequent tool changes due to wear or overheating can disrupt surgical workflows. By reducing wear rates, UAD not only extends the lifespan of drill bits but also ensures consistent performance throughout the procedure. This advantage is particularly beneficial in

complex surgeries involving multiple drilling stages or prolonged exposure to high-stress environments [27, 30].

In dental implantology, UAD addresses challenges unique to drilling in jawbone structures, which often consist of both cortical and trabecular bone. Excessive forces or elevated temperatures in these regions can lead to delayed healing, microfractures, and even necrosis. UAD's precise control over drilling parameters minimizes these risks, enabling surgeons to achieve optimal implant integration. Additionally, by preserving bone density and minimizing bone resorption around the implant site, UAD ensures long-term stability and functionality of dental implants [13, 19].

While UAD's advantages are clear, its adoption in medical contexts faces some challenges. The optimization of parameters such as vibration amplitude, frequency, and rotational speed is critical to ensuring effective performance across different bone types. Improper settings can lead to suboptimal cutting efficiency or even instability during drilling. Furthermore, the cost of ultrasonic equipment and the need for specialized training present barriers to widespread clinical implementation, particularly in resource-limited settings. Future research should focus on refining UAD technologies to make them more accessible and adaptable to the unique demands of surgical applications [14].

In summary, UAD builds on the principles of standard VAD by introducing high-frequency oscillations that transform the cutting process. By reducing thrust force, enhancing chip management, and improving thermal control, UAD addresses many of the challenges outlined in Section 1.1.1 and Section 1.1.2, positioning itself as a highly effective solution for medical drilling applications. As advancements continue to refine this technology, UAD has the potential to become a standard in orthopedic and dental surgical procedures, offering safer, more efficient outcomes for patients.

1.1.4 Experimental studies in UAD

UAD has demonstrated significant advantages in experimental studies across a variety of materials and applications, reinforcing its potential as a transformative technology in machining. By superimposing high-frequency vibrations onto the drill bit during the drilling process, UAD enhances cutting efficiency while addressing key limitations of CD. These benefits, including reduced cutting forces, improved surface quality, and extended tool life, have been validated through numerous experimental investigations. This section synthesizes findings from UAD experiments, emphasizing its mechanisms, advantages, and applications across different domains.

The fundamental mechanism of UAD lies in the application of ultrasonic vibrations—typically above 20 kHz—to the drill bit during cutting. This oscillatory motion intermittently breaks contact between the drill bit and the material, reducing continuous engagement and friction. Neugebauer and Stoll [31] conducted experiments on aluminum alloys, reporting significant reductions in both axial and radial forces during drilling, which directly contributed to extended tool life compared to CD methods [32].

Similarly, Liao et al [33]. examined UAD in Inconel 718, a notoriously challenging material to machine due to its hardness and heat resistance, and observed a marked decrease in cutting forces and improved process efficiency [32]. These findings underscore UAD's ability to enhance tool performance and material machinability, even in high-performance materials.

Beyond force reduction, experimental studies consistently highlight the impact of UAD on surface quality. Chen et al. demonstrated that UAD produces superior surface finishes compared to CD, with smoother surfaces and fewer burrs observed in drilled holes [34]. The favorable chip formation mechanism facilitated by UAD is a critical factor, as smaller, fragmented chips are more easily evacuated from the drilling site, reducing friction and thermal accumulation. This advantage is particularly relevant in industries

such as aerospace and automotive, where the integrity of drilled surfaces directly affects component performance and longevity [34].

Thermal effects during drilling represent a critical challenge, particularly for heat-sensitive materials such as aluminum alloys and composite structures. Chu et al. validated that UAD significantly reduces the temperatures generated during drilling by disrupting continuous friction at the drill-material interface [35]. This reduction in thermal load not only preserves the material's microstructure but also enhances tool longevity by mitigating wear and heat-induced failure. These findings align with the challenges of bone drilling discussed in Section 1.1.1, where excessive heat can lead to thermal necrosis. The ability of UAD to manage temperatures effectively has implications for both industrial machining and surgical applications, such as drilling in cortical bone or other biological materials [35].

Composite materials, such as CFRPs, also benefit significantly from UAD, as demonstrated in the work of Makhdum et al. Their studies highlighted the challenges of drilling CFRPs, including delamination and poor chip evacuation due to the material's anisotropic properties (Makhdum et al., 2014). By introducing ultrasonic vibrations, UAD improved chip fragmentation and minimized delamination, resulting in cleaner cuts and enhanced mechanical integrity of the drilled holes. These findings are especially relevant in aerospace and automotive applications, where lightweight composites are increasingly used to optimize performance and fuel efficiency [36].

In the context of medical engineering, UAD has shown particular promise in orthopedic drilling applications. Alam et al. explored its use in drilling cortical bone and reported significant reductions in both thrust force and torque compared to CD [37]. This reduction in mechanical stress is critical for minimizing damage to surrounding tissues during surgical procedures. Furthermore, UAD's ability to maintain lower temperatures during drilling reduces the risk of thermal necrosis, supporting better osseointegration and

faster recovery times. These attributes make UAD a valuable tool for minimally invasive surgeries, where precision and control are paramount [37].

The productivity benefits of UAD are also noteworthy. Chu et al. reported faster penetration rates achieved with UAD without compromising surface quality or precision [35]. This efficiency not only translates to time and cost savings in high-volume production environments but also enhances workflow efficiency in surgical settings, where reduced procedural times can lower risks associated with prolonged operations. This dual advantage of speed and quality makes UAD particularly attractive for industries requiring both high precision and high throughput.

Experimental studies further emphasize UAD's versatility across a wide range of materials, including metals, composites, and biological tissues. For instance, in addition to its efficacy in machining hard-to-cut materials like Inconel and CFRPs, UAD has proven adaptable to softer materials where temperature and force control are critical. This adaptability allows UAD to seamlessly transition between different materials, minimizing the need for extensive retooling or process adjustments, a significant advantage in complex manufacturing environments [32, 36].

While the experimental evidence strongly supports the benefits of UAD, challenges remain in its broader adoption. The need for precise control over ultrasonic parameters, such as frequency and amplitude, is critical to achieving consistent performance across diverse applications. Additionally, the initial cost of ultrasonic equipment and the specialized training required for operators can be barriers to entry in resource-constrained settings. Future research should aim to address these limitations by optimizing equipment designs and developing user-friendly interfaces to facilitate wider adoption.

In conclusion, experimental studies in UAD validate its transformative potential in

both industrial and biomedical applications. By reducing cutting forces, managing thermal effects, and improving surface quality, UAD addresses many of the challenges inherent in CD methods. Its demonstrated success across a range of materials, from aerospace composites to cortical bone, highlights its versatility and effectiveness. As research continues to refine the technology and address existing challenges, UAD is poised to become an indispensable tool in precision drilling, offering enhanced performance, efficiency, and outcomes in diverse fields.

1.1.5 Numerical studies on UAD

Numerical studies on UAD have emerged as a pivotal component in advancing this technology, providing insights that complement experimental investigations. Through the application of computational methods, particularly Finite Element Analysis (FEA), researchers simulate the effects of ultrasonic vibrations on the drilling process. These studies focus on critical parameters such as cutting forces, chip formation, thermal dynamics, and machining accuracy. By validating experimental results and predicting performance across diverse operational scenarios, numerical analyses play a crucial role in refining UAD processes and tailoring them to meet the requirements of various materials and applications.

The reduction of cutting forces, a key advantage of UAD, has been extensively explored through numerical simulations. Li et al. performed a comprehensive numerical analysis of UAD on Ti6Al4V, a widely used aerospace alloy, demonstrating that ultrasonic vibrations lead to intermittent contact between the drill bit and the material, significantly reducing cutting forces compared to CD [38]. This reduction is attributed to the momentary disengagement of the tool from the workpiece, which lowers friction and enables smoother material removal. Numerical models in this study also revealed that specific ultrasonic frequencies and amplitudes maximize force reduction, providing a road map for

parameter optimization. Similarly, numerical models have provided insights into force distribution along the tool's cutting edge. These simulations enable researchers to pinpoint stress concentrations, allowing for design adjustments that reduce tool wear and enhance performance. The detailed force mapping offered by these models is particularly valuable for applications involving brittle materials, where excessive forces can result in cracking or other structural damage.

Chip formation and evacuation dynamics have also been studied extensively through numerical approaches. Chip formation and evacuation play a crucial role in determining the efficiency of drilling processes, and numerical studies have significantly contributed to understanding these dynamics in UAD. Wang et al. conducted simulations on Inconel 718, a heat-resistant superalloy, and found that ultrasonic vibrations promote the fragmentation of chips into smaller pieces, improving their evacuation from the drilling site (Wang et al., 2023). The models illustrated how ultrasonic vibrations disrupt continuous chip formation, reducing the risk of clogging and minimizing thrust and torque during drilling. Such insights are critical for deep-hole drilling applications, where chip management is often a challenge. Moreover, these studies have elucidated how specific vibration frequencies and amplitudes influence chip morphology. Smaller, discontinuous chips not only improve drilling stability but also reduce heat generation and tool wear, particularly in difficult-to-machine materials like composites and titanium alloys.

The accuracy and quality of drilled holes have also been another focus of numerical studies. Ma et al. [39] simulated UAD processes to assess their impact on hole circularity and dimensional accuracy, finding that ultrasonic vibrations significantly enhance these parameters compared to CD. The numerical models demonstrated that UAD minimizes oversize and improves the symmetry of drilled holes by reducing force fluctuations and thermal deformation. These findings are essential for applications requiring

high precision, such as medical implants and aerospace components. In addition to dimensional accuracy, numerical simulations have highlighted the role of ultrasonic vibrations in reducing surface roughness and burr formation. This aspect is particularly relevant in contexts where post-drilling operations must be minimized to save time and costs.

Thermal effects and stress distribution in UAD have been explored through numerical models, providing critical insights into heat generation and dissipation. Isobe et al. analyzed stress and thermal distributions in UAD, showing that ultrasonic vibrations significantly reduce localized heat buildup at the drill-workpiece interface [40]. This reduction in thermal load is attributed to the pulsed nature of ultrasonic vibrations, which disrupt continuous friction and allow for more effective heat dissipation. These findings are particularly valuable for materials prone to thermal degradation, such as polymers, composites, and biological tissues. Numerical studies have also explored the relationship between heat generation and material properties. By incorporating thermal conductivity, specific heat, and material density into their models, researchers have identified optimal vibration parameters that minimize thermal damage, ensuring the integrity of both the tool and the workpiece.

The integration of numerical simulations with experimental studies has further enhanced the reliability and applicability of UAD research. Alam et al. combined experimental data with numerical models to study thrust forces and torque in cortical bone drilling, demonstrating that UAD significantly reduces these parameters compared to conventional methods [37]. Their work underscored the importance of numerical models in predicting outcomes and refining parameters for surgical applications, where precision and tissue preservation are critical. Numerical studies also provide a cost-effective alternative for exploring parameter variations that may be challenging to replicate experimentally. By simulating multiple scenarios, researchers can narrow down optimal conditions before conducting physical trials, saving time and resources.

Advanced numerical techniques, particularly finite element analysis (FEA), have been central to UAD studies. FEA has enabled detailed analysis of cutting dynamics and material behavior. Mao used FEA to investigate the performance of UAD on CFRP, finding that ultrasonic vibrations significantly reduce axial forces and improve surface finish [41]. These simulations provided a comprehensive understanding of how ultrasonic parameters influence machining outcomes in composites, which are increasingly used in aerospace and automotive industries. In addition to mechanical modeling, numerical studies have incorporated fluid dynamics simulations to evaluate the interaction between ultrasonic vibrations and cooling fluids. These studies have shown that ultrasonic vibrations enhance the penetration and distribution of cooling agents, reducing localized heat buildup and prolonging tool life. This integration of thermal and mechanical modeling offers a holistic view of the UAD process, enabling further refinement of parameters for high-speed drilling applications.

Finally, material-specific numerical insights have highlighted UAD's potential for challenging materials, such as ceramics and brittle composites. Numerical modeling has shown that optimized ultrasonic parameters improve material removal rates, reduce tool wear, and minimize defect formation in these materials. The ability to simulate these interactions at a granular level allows manufacturers to tailor UAD processes for specific material properties, enhancing overall productivity and quality.

1.1.6 Parametric studies on UAD

Parametric studies on UAD have become a cornerstone of research aimed at enhancing the efficiency, precision, and adaptability of this advanced drilling technique. These studies delve into the effects of critical parameters—including ultrasonic frequency, amplitude, feed rate, and drilling speed—on performance metrics such as thrust force, surface quality, tool wear, and Material Removal Rate (MRR). Through systematic analysis

and experimental validation, researchers have gained invaluable insights into optimizing UAD for a variety of materials and applications.

One major theme in these studies is the reduction of thrust forces during drilling operations. The intermittent engagement of the drill bit with the material, enabled by ultrasonic vibrations, breaks the continuity of frictional contact, allowing for smoother cutting and reduced force requirements. [42] conducted experiments on aluminum and titanium alloys, demonstrating significant reductions in thrust forces—up to 30% compared to CD. These reductions are particularly critical in applications involving brittle or delicate materials, where excessive forces can lead to microcracking, delamination, or material failure. Lower thrust forces also contribute to longer tool life and reduced wear, as optimized ultrasonic amplitudes and frequencies minimize mechanical stress and heat generation at the cutting interface. This dual benefit enhances process efficiency and reduces operational costs, which is of particular importance in both industrial and medical contexts where tool precision and reliability are vital.

An additional focus has been the influence of ultrasonic excitation modes, such as axial, torsional, or combined vibrations, on drilling performance. [43] explored these effects and found that torsional vibrations were especially effective in enhancing surface finish and reducing tool wear, whereas axial vibrations were more effective in minimizing thrust force. These results underline the need to tailor excitation modes to specific materials and applications, whether in machining hard metals, composites, or biological tissues.

The interaction between ultrasonic frequency, feed rate, and drilling speed has also been investigated extensively. For instance, [35] applied a Grey-Based Taguchi method to identify optimal drilling parameters for deep-hole applications, concluding that higher ultrasonic frequencies combined with moderate feed rates produced better results. Their findings showed reductions in drilling torque, improvements in material removal rates,

and enhanced dimensional accuracy. Such parameter tuning is particularly important for applications demanding high precision, such as orthopedic surgeries or the manufacturing of aerospace components, where minimal thermal and mechanical damage is essential for preserving workpiece integrity.

Studies focusing on composite materials, including CFRP, have shown that UAD offers considerable advantages for these difficult-to-machine substrates. [44] investigated the role of amplitude ratios in longitudinal–torsional coupled UAD of CFRPs and reported that higher amplitude ratios reduced thrust force, burr formation, and surface roughness, leading to better hole quality. Similarly, Feng and Jiao [28] examined CFRP exit damage and demonstrated that slower drilling speeds combined with higher ultrasonic frequencies reduced exit tearing and burr formation. These results emphasize the importance of synchronized parameter optimization for successful composite machining.

The management of thermal effects has also received significant attention. Ultrasonic vibrations have been shown to reduce heat generation by disrupting continuous frictional contact. Alam et al. [37] investigated this in the context of cortical bone drilling and observed that reduced friction and improved chip evacuation helped minimize thermal damage. Such thermal management is critical in medical applications to avoid tissue necrosis and in industrial contexts to prevent thermal deformation, thereby ensuring dimensional accuracy and surface quality.

Research on chip formation and evacuation dynamics has highlighted that higher ultrasonic amplitudes promote discontinuous chip formation. Azghandi and Razfar [32] showed that these smaller, fragmented chips are easier to remove, which helps prevent tool clogging and supports smoother drilling operations, particularly in deep-hole or dense material applications.

Parametric studies have consistently demonstrated that UAD enhances hole quality, improving circularity, dimensional precision, and surface finish. For example, Yang

et al. [45] reported that optimized amplitude and feed rate settings significantly reduced oversize and improved hole symmetry, which is critical for applications like orthopedic implants and aerospace assemblies where tight tolerances are required.

Alongside experimental investigations, modeling efforts have provided further insights into the optimization of UAD parameters. Yuan et al. [46] developed predictive models for cutting forces in the UAD of ceramics, identifying spindle speed, amplitude, and static pressure as key factors influencing performance. Such models offer a cost-effective means of evaluating parameter interactions and refining settings without extensive physical trials.

The adaptability of UAD across various challenging materials has also been confirmed. For example, Mikhailova et al. [47] studied marble drilling and demonstrated that appropriate ultrasonic parameters significantly reduced machining-induced damage. These findings illustrate how UAD can be successfully applied to brittle, anisotropic, or otherwise difficult-to-machine materials, supporting applications from architectural stonework to advanced manufacturing processes.

1.2 Problem Description

The drilling process in dental implantology presents significant challenges due to the mechanical and thermal stresses generated during CD. High thrust forces and elevated temperatures are inherent to CD and can have detrimental effects on the bone's structural integrity and the long-term stability of the implant. Excessive temperature, for example, can result in thermal necrosis—an irreversible condition where bone tissue is damaged when temperatures exceed 47°C. This is particularly critical in dental implantology, where maintaining a stable bone-implant interface is essential for successful osseointegration. Elevated temperatures, combined with mechanical stresses, have been shown to induce microcracks within the bone matrix, which impede the healing process and compromise

the strength of the bone-implant bond [48].

Adding to this complexity is the heterogeneous structure of the jawbone, which comprises both cortical (dense) and trabecular (spongy) bone. Unlike long bones, where cortical bone predominates, the jawbone's mixed composition necessitates precise control of drilling parameters to avoid microdamage. Excessive forces or uncontrolled drilling can undermine the integrity of the implant site and increase the risk of implant failure. While CD remains widely used, its inherent limitations—primarily high thermal and mechanical stresses—underscore the need for safer and more efficient drilling techniques that can preserve bone integrity.

In response to these challenges, UAD has emerged as a promising alternative to CD. By superimposing high-frequency vibrations along the drill axis, UAD intermittently reduces the contact between the drill bit and the bone, thereby minimizing friction and reducing both thrust force and heat generation. Studies on UAD in non-biological materials have demonstrated significant benefits, including lower cutting forces, improved thermal control, and enhanced tool performance [48, 49]. These findings suggest that UAD could offer similar advantages in dental implantology, where reducing mechanical and thermal stresses is paramount. However, the application of UAD in bone drilling is not straightforward due to the unique mechanical behavior of cortical and trabecular bone, as well as the dynamic response of bone tissue to cyclic loading.

Despite its potential, the application of UAD in dental implantology remains underexplored. Numerical simulations have predicted reductions in drilling forces and temperatures with UAD compared to CD; however, these studies often fail to fully capture the complexities of the jawbone's heterogeneous composition. Additionally, the interaction of ultrasonic vibrations with bone tissue under cyclic loading requires further investigation to assess its effects on structural integrity and osseointegration. Crucially, there is a lack of comprehensive experimental data to validate these theoretical predictions and

evaluate the clinical feasibility of UAD in dental applications.

This absence of detailed studies highlights a critical gap in the current research. To address this, systematic experimental investigations are required to quantify the effects of UAD on drilling forces, heat generation, and the mechanical integrity of the bone-implant interface. Furthermore, validated numerical models that account for the dual composition of the jawbone are essential for optimizing UAD parameters, such as frequency and amplitude, for clinical applications. Bridging this research gap will provide vital insights into the effectiveness of UAD and its potential to revolutionize dental implant procedures by offering a safer and more efficient alternative to CD methods.

1.3 Scope of the Study

This study investigates the mechanical and thermal behavior of bone during drilling for dental implantology, focusing on CD and UAD. The experiments were conducted *ex vivo* using prepared bone specimens to ensure controlled conditions and repeatable measurements. This approach enabled the evaluation of thrust forces, thermal effects, and chip formation under realistic drilling scenarios.

A parametric study was carried out to analyze the influence of key UAD parameters, such as vibration frequency, amplitude, and rotational speed, on the mechanical and thermal response of bone. FEM simulations were developed to complement the *ex vivo* experiments, incorporating the Johnson-Cook material and damage models to simulate realistic bone behavior and validate experimental results.

The findings provide a comparative understanding of UAD and CD techniques, contributing to improved insights into their performance in dental drilling applications. This work supports future studies aimed at enhancing the safety and effectiveness of implant procedures.

2. THEORETICAL BACKGROUND AND NUMERICAL MODELING

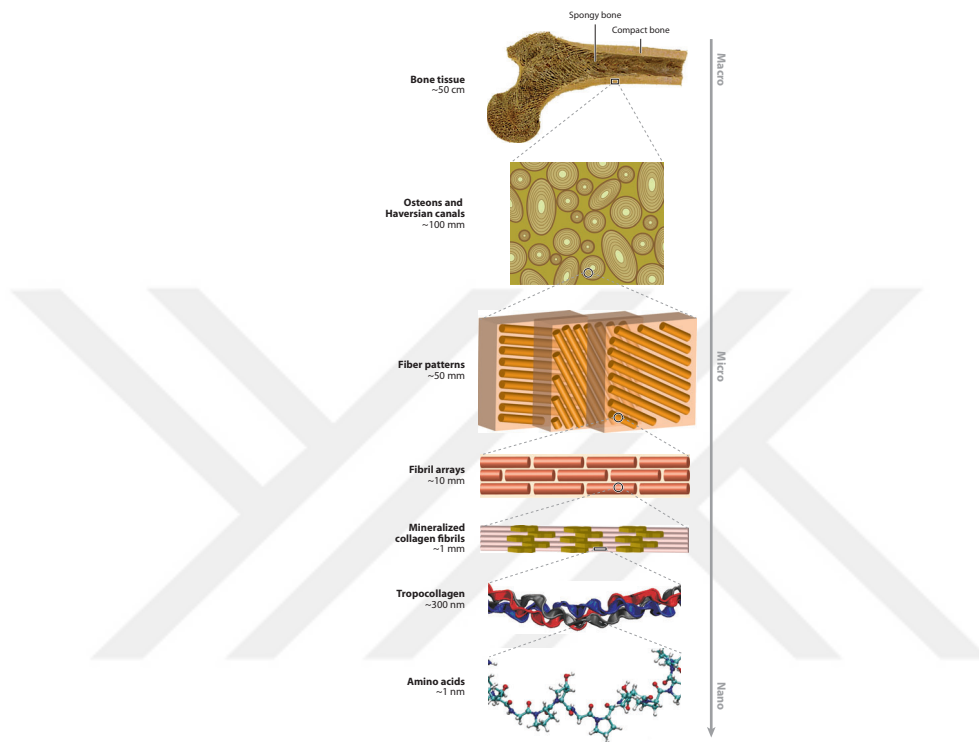
This chapter provides a comprehensive overview of the methodologies and theoretical frameworks that underpin the study. The discussion begins with an in-depth exploration of bone structure and mechanics, highlighting its hierarchical organization and adaptive properties. Subsequently, advanced material models, such as the Johnson-Cook (JC) and JC Damage models, are introduced to describe the mechanical behavior of materials under extreme loading conditions. The chapter also delves into key drilling parameters, tool geometry, and thermal effects, with a particular focus on VAD techniques, which are evaluated for their potential to enhance efficiency and reduce mechanical and thermal stresses. By integrating theoretical and empirical insights, this chapter lays the groundwork for understanding the interactions between materials and processes, providing a foundation for the subsequent analysis and experimentation.

2.1 Bone Structure and Mechanics

Bone is a complex and dynamic tissue that serves vital mechanical functions, including structural support, protection of internal organs, and facilitation of movement. From a mechanical perspective, bone is classified into two primary types: cortical (compact) bone and trabecular (cancellous) bone is depicted in Figure 2.1. Cortical bone forms the dense, rigid outer shell, providing strength and resistance to compressive forces, while trabecular bone, located within the interior, is characterized by a porous, lattice-like structure. This porous architecture not only reduces the weight of the skeleton but also enhances energy absorption and shock resistance [50, 51, 52]. The hierarchical organization of these two bone types allows for an optimal balance between strength and lightness, enabling the skeleton to withstand the diverse mechanical loads encountered during daily

activities and high-impact events [52, 53].

Figure 2.1: *Hierarchical structure of bone [50]*



The mechanical performance of bone is inherently linked to its microstructure, which comprises an intricate composite of collagen fibers, mineralized hydroxyapatite, and biological constituents such as proteoglycans and water [54, 55]. The collagen matrix, oriented along the primary stress directions, provides tensile strength, enabling bone to resist deformation under pulling forces. Hydroxyapatite, a calcium-phosphate-based mineral, imparts compressive strength, allowing bone to sustain substantial loads without collapse [53, 55]. This composite design endows bone with exceptional toughness, defined as the ability to absorb energy and deform without catastrophic failure. Such toughness is achieved through hierarchical mechanisms, including microcracking and fibril bridging,

which dissipate stress and prevent the propagation of fractures [50, 53]. Importantly, variations in collagen alignment, mineral density, or microstructural integrity can profoundly affect bone's mechanical properties, influencing its resilience under physiological and pathological conditions [51, 56].

Bone is a living tissue that continuously remodels in response to mechanical stimuli, a process governed by the coordinated activity of osteoblasts, which form new bone, and osteoclasts, which resorb old bone [57, 58]. This dynamic remodeling process enables bone to adapt its structure to changing mechanical environments, optimizing strength and durability. For example, increased mechanical loading stimulates bone formation, resulting in denser and stronger bone, whereas reduced loading, as seen in immobilization or microgravity conditions, leads to resorption and reduced mechanical strength [57, 59]. The adaptability of bone is particularly critical in aging and disease, where alterations in remodeling processes can lead to fragility, reduced mass, and increased fracture risk [52, 60].

In addition to its structural functions, bone plays a fundamental role in the biomechanics of movement. Acting as a lever system, it interacts with muscles and joints to enable locomotion and maintain balance. Bone's mechanical properties are crucial for absorbing forces during activities such as walking, running, and jumping, thereby protecting the body from injury [52, 61]. Furthermore, bone's ability to adapt to mechanical demands supports physical performance and reduces the risk of injury, emphasizing its critical role in overall skeletal health [52, 60]. Understanding the intricate relationship between bone structure, mechanical properties, and adaptation mechanisms is essential for advancing research in orthopedics, tissue engineering, and biomechanics, ultimately informing the development of innovative therapies and interventions.

2.1.1 The Johnson-Cook Material Model

The JC material model is an empirical constitutive framework extensively used in simulations involving metals subjected to high strains, elevated strain rates, and elevated temperatures. Its versatility makes it particularly valuable in extreme loading conditions, including impact events, ballistic penetration, machining, metal forming, and explosive loading. By capturing the essential aspects of plastic deformation under complex conditions, the JC model is a widely adopted choice for finite element analysis of dynamic processes [62, 63].

The JC model incorporates the effects of strain hardening, strain rate sensitivity, and thermal softening into a single constitutive equation. As shown in Equation (2.1), the flow stress σ is defined as:

$$\sigma = (A + B \cdot \varepsilon_p^n) \cdot \left(1 + C \cdot \ln \left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)\right) \cdot \left(1 - \left(\frac{T - T_{\text{room}}}{T_{\text{melt}} - T_{\text{room}}}\right)^m\right) \quad (2.1)$$

Here, A represents the material's yield stress under quasi-static conditions, B is the hardening modulus describing the increase in strength with plastic strain, and n is the strain hardening exponent shaping the stress-strain curve. The strain rate sensitivity coefficient C quantifies the material's resistance to deformation at higher strain rates, while m is the thermal softening exponent indicating how material strength diminishes with rising temperature. Additional variables include ε_p , the equivalent plastic strain; $\dot{\varepsilon}$, the equivalent plastic strain rate; $\dot{\varepsilon}_0$, the reference strain rate typically set at 1 s^{-1} ; T , the current temperature; T_{room} , the room temperature; and T_{melt} , the melting temperature. Each term in the equation reflects a distinct material behavior: strain hardening accounts for the strengthening effect due to plastic deformation, strain rate sensitivity models increased resistance to deformation at elevated strain rates, and thermal softening describes the reduction in strength as the temperature approaches the material's melting point [62].

The parameters within the JC model provide critical insights into material behavior under mechanical and thermal loads. The yield stress (A) defines the initial resistance to plastic deformation, while the hardening modulus (B) and strain hardening exponent (n) determine the rate at which material strength increases with accumulated plastic strain. The strain rate sensitivity coefficient (C) reflects how deformation resistance varies with the rate of loading, a crucial factor in high-speed processes where dislocation motion is restricted. The thermal softening exponent (m) characterizes the material's susceptibility to strength reduction as the temperature rises, with higher values indicating greater sensitivity to thermal effects [64]. These parameters are typically determined experimentally through tests conducted at varying strain rates and temperatures to ensure accurate calibration for the material of interest.

The JC model finds extensive applications across diverse fields. It is used in ballistic impact simulations to capture the effects of rapid deformation and thermal softening in both armor and penetrator materials. In metal cutting and machining, the model predicts stresses, strains, and temperatures in tools and workpieces, providing insights into wear and failure mechanisms [65]. Similarly, it is applied in crashworthiness analysis within the automotive and aerospace industries, where materials experience high strain rates and thermal effects due to deformation and friction. Additionally, the model proves effective in explosive and blast loading scenarios, simulating the rapid deformation and temperature rise in materials subjected to such extreme conditions [66].

Despite its advantages, the JC model has limitations. Being an empirical model, its parameters are derived from experimental data, which restricts its accuracy to the tested range. Extrapolation to conditions beyond this range can introduce errors. Moreover, the model does not account for microstructural phenomena, such as phase transformations, that may occur under extreme conditions. Furthermore, the standard JC formulation predicts plastic deformation but lacks the capability to model damage or failure. Extensions

like the JC Damage model address this limitation by incorporating damage criteria based on stress triaxiality, strain rate, and temperature [67]. Despite these constraints, the JC model remains a robust and widely adopted tool for understanding and simulating material behavior under dynamic conditions.

2.1.2 Johnson-Cook Damage Model

The JC damage model extends the original formulation to predict material failure. Damage initiation in this model is based on an additional equation that considers stress triaxiality, strain rate, and temperature, as given in Equation (2.2):

$$\varepsilon_p^f = (d_1 + d_2 e^{d_3 \eta}) \cdot \left(1 + d_4 \ln \left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0} \right) \right) \cdot \left(1 + d_5 \frac{T - T_{\text{room}}}{T_{\text{melt}} - T_{\text{room}}} \right) \quad (2.2)$$

where:

- d_1 through d_5 are damage constants, each defining the material's sensitivity to different aspects of deformation,
- η is the stress triaxiality, representing the ratio of hydrostatic stress to equivalent von Mises stress.

In this extended model, damage accumulates according to a cumulative rule, and failure occurs when the damage parameter D reaches a critical value of 1. This formulation enables realistic simulation of crack initiation and growth, particularly under complex loading conditions [68, 69].

2.2 Drilling Parameters

The effectiveness of drilling, including hole quality, material removal rate, and tool life, depends significantly on various drilling parameters. Proper selection and control

of these parameters are essential to optimize the process, improve efficiency, and prevent defects such as burr formation, poor surface finish, and thermal damage.

The primary drilling parameters include spindle speed, feed rate, and drill diameter, each of which directly influences the cutting forces, temperature, surface integrity, and efficiency of the drilling process. Spindle speed, measured in Revolutions Per Minute (RPM), determines the cutting speed at the drill's edge, affecting both heat generation and material removal rate. Feed rate, often specified in millimeters per revolution (mm/rev) or millimeters per minute (mm/min), controls the advancement of the drill into the material per unit of time. A higher feed rate increases the material removal rate but may lead to greater cutting forces, tool wear, and potential surface damage. Drill diameter influences both the hole dimensions and the torque required; larger diameters demand higher torque and produce more material resistance, thus requiring careful management to avoid tool breakage [70].

In addition to these primary parameters, cutting fluid application (coolant) and drill geometry also play vital roles in the drilling process. Cutting fluids help reduce the temperature and friction at the cutting interface, improving tool life and surface finish. Drill geometry, which includes parameters such as point angle, helix angle, and margin width, influences chip formation and evacuation, affecting drilling efficiency and quality. Optimizing these secondary parameters alongside the primary ones allows for smoother chip flow, reduced tool wear, and enhanced hole quality [70].

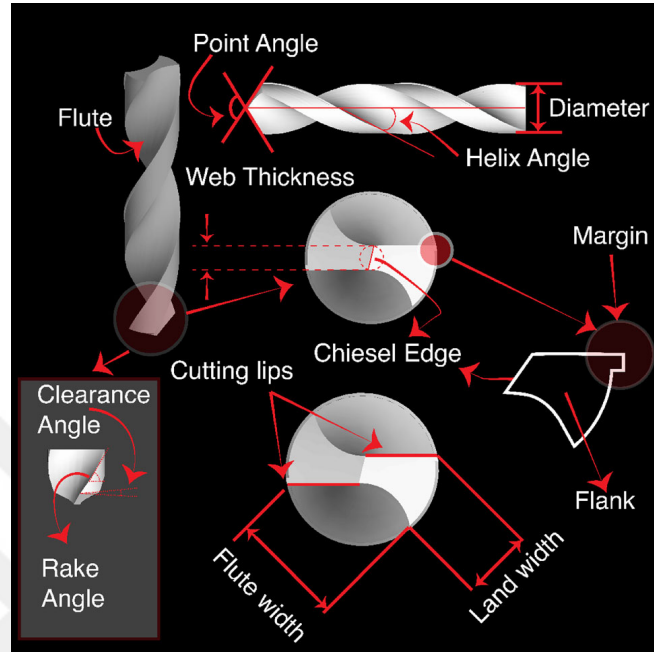
In advanced applications, particularly in drilling difficult-to-machine materials like titanium alloys, carbon fiber composites, and dense bone structures, VAD and UAD have emerged as effective techniques. These methods superimpose oscillations on the drill bit, reducing cutting forces, enhancing chip evacuation, and lowering the temperature at the drill-material interface, thereby extending tool life and improving hole quality [71].

Thoughtful selection of drilling parameters is crucial for achieving high-quality holes, minimizing tool wear, and enhancing productivity. Understanding the influence of each parameter on the drilling outcome is fundamental to advancing drilling technology and improving manufacturing processes.

2.2.1 Drill Geometry

In medical applications, such as orthopedic and dental surgeries, drill geometry plays a critical role in achieving precise, safe, and efficient drilling. The unique characteristics of human bone, along with the need to avoid damage to surrounding tissues, necessitate specific design features in medical drill bits. The point angle of the drill tip is designed to facilitate accurate entry into bone with minimal risk of slippage as show in Figure 2.2. In medical procedures, a sharper point angle is often preferred as it enhances precision and control, particularly when drilling near sensitive areas like nerves or blood vessels [72].

Figure 2.2: *Anatomy of a surgical drill bit [72]*



The helix angle and flute design are equally important as they significantly influence chip removal. In bone drilling, efficient evacuation of bone debris is essential to prevent clogging, reduce friction, and minimize heat generation. A high helix angle combined with an optimized flute design ensures smooth removal of bone chips, thereby reducing the risk of overheating and thermal damage, which could impair bone healing [71]. Additionally, the sharpness of the cutting edge and the relief angle play a vital role in the drill's cutting efficiency and the quality of the hole surface. Medical drill bits are typically designed with a fine cutting edge to lower cutting forces and minimize damage to the surrounding bone. Optimized relief angles further help in reducing excessive friction, minimizing the likelihood of thermal necrosis [72].

Self-centering features are often incorporated into the design of medical drill tips to enhance stability and ensure precise alignment. These features are particularly crucial

in minimally invasive procedures, where maintaining accuracy is essential. Specialized tip geometries, such as pyramid or conical shapes, help ensure the drill stays on course and does not deviate from the target path, which is critical for surgical precision [73].

Furthermore, some medical drill bits are equipped with integrated cooling channels or irrigation holes that allow saline or cooling fluids to flow through the drill bit during operation. This design effectively dissipates heat and flushes out bone debris, reducing the risk of thermal damage while also improving visibility in the surgical field [70]. The geometry of medical drill bits is optimized to achieve high precision while minimizing thermal effects and mechanical trauma to bone tissue. These design considerations are fundamental to ensuring patient safety, preserving bone integrity, and promoting faster recovery by preventing unnecessary damage during surgical procedures.

2.2.2 Thermal Effects in Drilling

In drilling, the interaction between the cutting tool and the workpiece results in significant energy dissipation, primarily in the form of heat. This heat generation is influenced by material properties, drilling parameters, and tool geometry, and understanding the underlying mechanisms is essential for predicting temperatures at the cutting interface, optimizing processes, and minimizing thermal damage [74, 75].

Heat generation in drilling arises from three primary mechanisms: frictional heat, plastic deformation heat, and chip formation heat. Frictional heat occurs at the interface between the drill bit and the workpiece as the cutting edge rotates and rubs against the material, generating significant thermal energy due to frictional forces. The intensity of this heat is influenced by the friction coefficient, cutting parameters such as feed rate and spindle speed, and material properties [76]. Simultaneously, plastic deformation heat develops in the shear zone as the material is plastically deformed to form chips. This process involves significant energy dissipation due to dislocation movement and internal friction

within the material. The sliding action of chips along the rake face further generates additional frictional heat, exacerbating the thermal conditions at the cutting interface.

Heat generation during drilling occurs in three main zones: the primary shear zone, the secondary shear zone, and the flank zone. The primary shear zone, located near the cutting edge, is where intense shearing of the material takes place, resulting in significant plastic deformation heat. The secondary shear zone is located along the rake face of the drill, where chips slide and adhere, producing additional frictional heat. Finally, the flank zone, located on the clearance face of the drill bit, generates heat due to the rubbing action between the tool and the newly cut surface of the workpiece [74, 77]. The cumulative effect of these zones results in a high-temperature environment that affects tool wear, material properties, and the quality of the drilled hole.

The rate of heat generation in drilling can be estimated by correlating mechanical power input to thermal energy output. The total power input, P , is given as in Equation (2.3):

$$P = T \cdot \omega, \quad (2.3)$$

where T is the torque required to rotate the drill bit, and ω is the angular velocity, expressed as in Equation (2.4):

$$\omega = \frac{2\pi N}{60}. \quad (2.4)$$

Here, N is the spindle speed in RPM. Assuming that most of the mechanical power is converted into heat, the heat generation rate Q can be approximated as in Equation (2.5):

$$Q = P = T \cdot \omega. \quad (2.5)$$

The heat generated is distributed among the tool, workpiece, and chips. The fractions of heat absorbed by each component depend on their thermal properties, including conductivity and diffusivity. For example, materials with low thermal conductivity, such

as titanium alloys or bone, tend to retain heat near the cutting zone, leading to higher localized temperatures. In contrast, metals with high thermal conductivity, like aluminum, dissipate heat more efficiently, reducing the thermal load at the interface [75, 76].

Temperature rise at the tool-workpiece interface can be approximated using Equation (2.6):

$$\Delta T = \frac{Q \cdot \eta}{A \cdot h}, \quad (2.6)$$

where A is the contact area, h is the heat transfer coefficient, and η is the fraction of heat entering the workpiece. For practical analysis, models such as Jaeger's Moving Heat Source Model and Rosenthal's Temperature Model are widely used. Jaeger's model assumes a continuous moving heat source and expresses the temperature distribution in Equation (2.7):

$$T(x, y, z, t) = T_{\text{initial}} + \frac{Q}{2\pi k} \int_{-\infty}^{\infty} \frac{e^{-\frac{(x-vt)^2 + y^2 + z^2}{4\alpha t}}}{t} dt, \quad (2.7)$$

where k is the material's thermal conductivity, v is the heat source velocity, and α is the thermal diffusivity [78]. Rosenthal's model simplifies the scenario by considering a point heat source and expresses the temperature in Equation (2.8):

$$T = T_{\infty} + \frac{Q}{2\pi k R} e^{-\frac{vR}{2\alpha}}, \quad (2.8)$$

where R is the radial distance from the heat source, and T_{∞} is the ambient temperature.

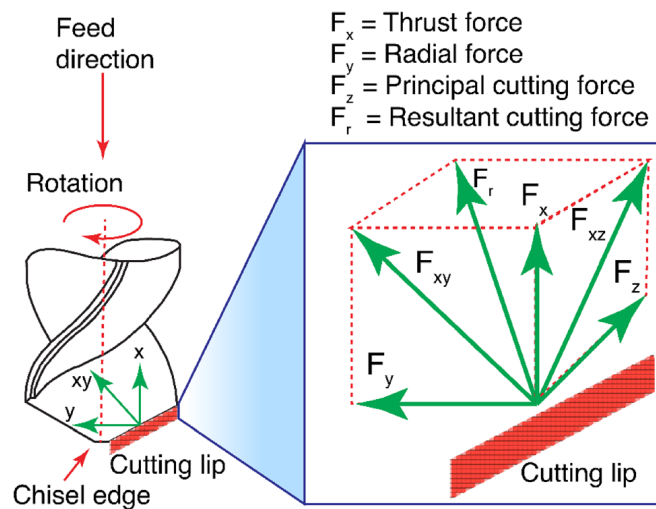
The thermal behavior during drilling is influenced by several factors, including material properties, tool geometry, and drilling parameters. Materials with low thermal conductivity are prone to localized heating, while tool geometries with optimized rake angles and flute designs facilitate efficient chip evacuation, minimizing thermal buildup. Drilling parameters such as spindle speed, feed rate, and cutting forces directly influence heat generation, with higher speeds increasing friction and thermal loads [74, 77]. The application of cooling methods, such as cutting fluids or irrigation in medical drilling,

plays a critical role in dissipating heat and preventing thermal damage to the workpiece and tool.

2.2.3 Thrust Force in Drilling

In drilling, thrust force, also referred to as axial force, is the force applied along the axis of the drill bit that drives it into the material as shown in Figure 2.3. Thrust force plays a critical role in determining the effectiveness, precision, and quality of the drilling process, as well as the potential for damage to the workpiece or surrounding structures. High thrust forces can lead to tool wear, excessive heat generation, and structural damage, while insufficient thrust can cause the drill to slip or deviate from its intended path. Thrust force is generated by the combined action of the cutting edges, chisel edge, and tool geometry, which work collectively to penetrate the material and remove chips [74, 75].

Figure 2.3: Force systems on the cutting lips of a drill bit [72]



The cutting edges on the drill bit periphery contribute significantly to thrust force by shearing material, while the chisel edge, located at the drill tip center, is less efficient.

Instead of shearing, the chisel edge extrudes and deforms the material directly ahead of it, encountering significant resistance and producing a majority of the thrust force [75]. Drill geometry, including the rake angle and clearance angle, also influences thrust force by determining the material's ease of shearing and reducing unnecessary friction.

The thrust force, denoted as F_z , can be theoretically estimated based on cutting mechanics. A commonly used empirical relationship is Equation (2.9):

$$F_z = K_f \cdot f^n \cdot d, \quad (2.9)$$

where K_f is the specific thrust force constant dependent on material properties and tool geometry, f is the feed rate, n is an empirically derived exponent (typically near 1), and d is the drill diameter. For a detailed understanding, thrust force is often divided into components generated by the cutting edges and the chisel edge. The cutting edge force, $F_{z,c}$, is expressed in Equation (2.10):

$$F_{z,c} = 2 \cdot K_c \cdot f \cdot r_c, \quad (2.10)$$

where K_c is the specific cutting force, f is the feed per revolution, and r_c is the radial distance to the cutting edge. Meanwhile, the chisel edge force, $F_{z,e}$, can be approximated as Equation (2.11):

$$F_{z,e} = K_e \cdot A_e, \quad (2.11)$$

where K_e is the specific chisel edge force and A_e is the chisel edge cross-sectional area [76]. Combining these components, the total thrust force F_z is expressed in Equation (2.12):

$$F_z = 2 \cdot K_c \cdot f \cdot r_c + K_e \cdot A_e. \quad (2.12)$$

The Shaw model further refines thrust force estimation by incorporating parameters like shear strength σ_s , point angle θ , and chisel edge length L Equation (2.13):

$$F_z = (2 \cdot f \cdot d \cdot \sigma_s) \cdot \left(\tan \frac{\theta}{2} + \frac{d}{3L} \right). \quad (2.13)$$

Thrust force is influenced by material properties, tool geometry, and operating parameters. Harder and stronger materials necessitate higher forces, while optimized drill geometries—such as sharper point angles and reduced chisel edge lengths—help minimize resistance. Operating parameters, including feed rate and spindle speed, directly impact force magnitudes, with larger feed rates and diameters increasing material engagement and thrust force. Monitoring thrust force is especially important in precision drilling to ensure the quality of the procedure and avoid complications such as tool deflection or thermal damage [74].

2.3 Vibration-Assisted Drilling Formulation

VAD is a technique that superimposes controlled vibrations onto the conventional drilling motion, typically in the axial (longitudinal) direction. This superimposed vibration results in an intermittent cutting action, where the drill bit periodically disengages from the material, reducing the continuous contact time between the tool and the workpiece. This intermittent contact reduces cutting forces, improves chip evacuation, and lowers the temperature at the cutting interface, leading to better hole quality and extended tool life.

In VAD, two primary types of vibration are generally applied: Low-Frequency VAD and UAD. Low-Frequency-VAD typically employs frequencies below 1 kHz and is predominantly used for machining metals, where its advantages include improved cutting efficiency and tool life. On the other hand, UAD involves frequencies above 20 kHz and is commonly applied for brittle materials or precision applications, such as bone drilling, due to its capability to minimize material damage and enhance hole quality.

The mechanics of VAD rely on the oscillatory motion of the drill bit superimposed on its standard rotational motion. This combination facilitates intermittent cutting, natural cooling between engagements, and efficient chip fragmentation, which collectively

result in reduced cutting forces, enhanced surface finish, and improved overall drilling performance.

2.3.1 Mechanics and Key Parameters of Vibration-Assisted Drilling

In VAD, the drill bit undergoes an oscillatory motion along its axis in addition to its rotational movement. This combined motion results in a cyclical engagement and disengagement with the material. The intermittent cutting action achieved through this oscillatory motion reduces the continuous frictional contact between the cutting tool and the material. This mechanism allows for natural cooling between engagements and minimizes heat buildup, which is especially advantageous in precision applications and when working with heat-sensitive materials.

One of the key outcomes of VAD is the significant reduction in average cutting forces. The disengagement of the tool during part of the oscillatory cycle decreases the force requirements, making it easier to machine hard materials while also extending tool life. Furthermore, the oscillatory motion aids in breaking the chips into smaller fragments, improving chip evacuation and reducing the risk of clogging in the cutting zone. This enhanced chip management contributes to better surface finishes, particularly when working with composite or metallic materials.

The performance of VAD is governed by several critical vibration parameters. Vibration frequency (f) determines the number of oscillations per second, with higher frequencies (e.g., ultrasonic) enabling finer intermittent cutting action, making it ideal for precision applications. Amplitude (A), which defines the peak displacement of the oscillation, plays a crucial role in determining the penetration depth per cycle. Larger amplitudes enhance chip removal efficiency and reduce cutting forces but must be optimized to avoid excessive tool wear or surface roughness issues.

Feed rate (f), the rate at which the drill advances into the material, must be synchronized with the vibration frequency and amplitude to achieve effective intermittent cutting. Similarly, cutting speed (V_c), the rotational speed of the drill, influences the interaction between the oscillatory motion and cutting forces. To maximize the benefits of VAD, the vibration amplitude should be sufficiently large to ensure complete disengagement of the drill bit from the material during each cycle. This synchronization of feed rate, frequency, and amplitude is key to achieving reduced cutting forces, improved chip management, and superior hole quality.

2.3.2 *Mathematical Formulation and Effects of Vibration Parameters in VAD*

VAD enhances conventional drilling by superimposing a vibratory motion onto the drill bit's feed movement, resulting in intermittent cutting that improves chip evacuation, reduces cutting forces, and enhances surface quality. The drill bit's displacement, $Z(t)$, can be mathematically represented in Equation (2.14):

$$Z(t) = f \cdot t + A \cdot \sin(2\pi f_v \cdot t) \quad (2.14)$$

where:

- f is the constant feed rate,
- A is the vibration amplitude,
- f_v is the vibration frequency,
- t is time.

This equation illustrates how the combination of linear feed and sinusoidal vibration leads to periodic disengagements between the tool and workpiece, facilitating improved chip breaking and evacuation [79].

The intermittent contact in VAD significantly influences cutting forces. The average thrust force, $F_{z,\text{avg}}$, is generally reduced compared to conventional drilling. This reduction can be approximated in Equation (2.15):

$$F_{z,\text{avg}} = F_{z,\text{conv}} \times \left(1 - \frac{\Delta t}{T}\right) \quad (2.15)$$

where:

- $F_{z,\text{conv}}$ is the thrust force in conventional drilling,
- Δt is the disengagement time per vibration cycle,
- $T = \frac{1}{f_v}$ is the period of one vibration cycle.

The term $\left(1 - \frac{\Delta t}{T}\right)$ represents the proportion of time the tool is engaged with the workpiece, indicating that higher vibration frequencies and amplitudes, which increase Δt , lead to greater reductions in thrust force [80].

Effective chip formation and evacuation are critical in VAD. The vibratory motion induces cyclic loading, promoting the formation of shorter, more manageable chips, which are essential for maintaining surface integrity and preventing tool wear [81].

Thermal aspects are also impacted by VAD. The intermittent cutting reduces heat generation, minimizing thermal damage to both the tool and workpiece. This is particularly beneficial when machining materials sensitive to temperature variations [82].

The performance of VAD is highly dependent on the selection of vibration parameters:

- **Frequency (f_v):** Higher frequencies result in more frequent tool disengagements, enhancing chip breakage and reducing cutting forces. However, excessively high frequencies may require specialized equipment and can lead to increased tool wear [83].

- **Amplitude (A):** Larger amplitudes increase the depth of the vibratory motion, improving chip fragmentation. Nonetheless, too large an amplitude can cause tool instability and affect dimensional accuracy [79].

Here is the revised version of the explanatory section in LaTeX format, suitable for direct integration into your thesis document.

2.4 Summary

This chapter has presented the theoretical background and methodological framework necessary for understanding the mechanical and thermal behavior of bone during drilling, particularly with the implementation of UAD. The critical aspects of bone mechanics, material modeling, and drilling parameters were detailed to establish the foundation for both experimental and numerical investigations.

The importance of bone structure and mechanics was emphasized, particularly the distinction between cortical and trabecular bone, which exhibit differing responses to mechanical stresses. The application of the JC material model and the JC damage model provides an accurate representation of bone behavior under the forces and temperatures generated during drilling. These models are pivotal for predicting mechanical responses and evaluating the potential for microdamage and thermal necrosis.

Additionally, the chapter discussed the significance of drilling parameters—such as rotational speed, feed rate, and drill geometry—on force generation and thermal accumulation during conventional drilling (CD). A theoretical analysis of the thermal effects arising from frictional heat highlighted the need to mitigate temperatures exceeding critical thresholds to prevent thermal osteonecrosis.

The mechanics and formulations of UAD were presented, illustrating its advantages over conventional methods. By introducing high-frequency vibrations into the drilling process, UAD reduces thrust forces, enhances chip evacuation, and minimizes

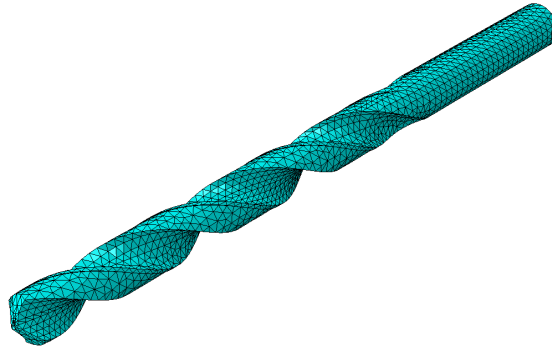
heat generation, which are critical for preserving bone integrity and ensuring successful implant integration. Key UAD parameters, including vibration amplitude, frequency, and rotational speed, were discussed in detail, as their optimization is essential for achieving the desired mechanical and thermal outcomes.

The entire theoretical background established in this chapter, including the JC material model, damage criteria, and thermal effects, has been implemented in the numerical modeling using ABAQUS. The FEM simulations integrate these theoretical principles to replicate realistic drilling scenarios, such as bone response to varying forces, thermal conditions, and vibration parameters. The accuracy of these simulations relies on the comprehensive framework presented here, ensuring that the numerical analysis reflects actual mechanical and thermal behaviors observed during drilling.

2.5 Numerical Modeling of Drilling Process

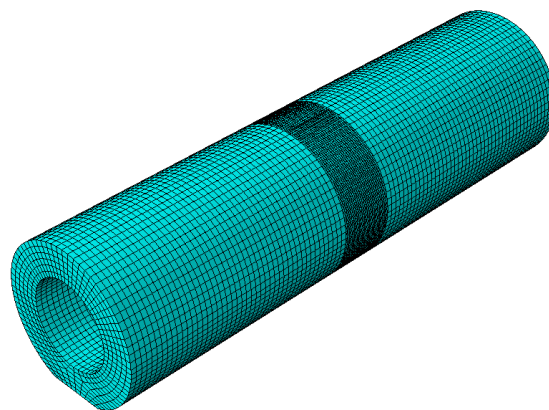
Numerical simulations of biological processes, such as drilling, offer a cost-effective and efficient approach to analyze underlying mechanics and optimize parameters. In this study, a FEM was developed to replicate the experimental setup and evaluate the mechanical interactions during drilling. The drill, with a diameter of 3 mm, was modeled as a rigid body using 4,564 R3D3 elements, which are 3-node, three-dimensional rigid triangular facet elements ideal for contact mechanics. The mesh resolution ranged from 0.1 mm to 0.5 mm, allowing for a detailed representation of the drill's geometry (Figure 2.4). The assumption of rigidity for the drill was validated by its negligible deformation under the applied loads during the drilling process.

Figure 2.4: *Finite Element Model of the Dental Drill*



The workpiece, representing the bone specimen, was modeled as a cylindrical structure with an inner diameter of 4 mm, an outer diameter of 7 mm, and a length of 50 mm, consistent with the experimental specimen dimensions. The finite element mesh consisted of 98,315 C3D8R elements, which are 8-node linear brick elements with reduced integration and hourglass control. Each element had 24 Degree of Freedom (DOF), derived from its 8 nodes, with each node contributing 3 translational DOFs in the x , y , and z directions. These elements were chosen for their computational efficiency and ability to capture large deformations and stress distributions accurately (Figure 2.5).

Figure 2.5: *Finite Element Model of the Bone Specimen*



The material properties of the bone were assigned using the JC plasticity model,

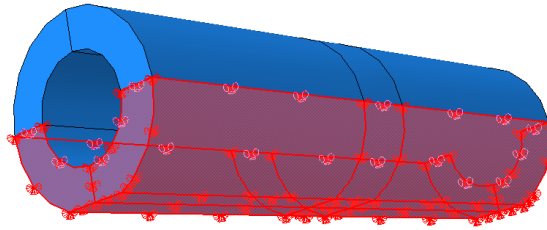
which accounts for strain hardening, strain rate sensitivity, and thermal softening to represent biological tissues under dynamic loading.[37] Table 2.1 summarizes the elastic, thermal, and plastic parameters used in the simulation. The mesh size of the bone was refined to 0.5 mm near the drilling interface, ensuring high-resolution representation of stresses and strains in the regions of significant deformation. The mesh density was increased near the drilling interface to capture the high gradients of stress and strain effectively.

Table 2.1: *Material Properties of Bone [37]*

Property	Elastic and Thermal Properties	Plastic Properties (Johnson-Cook Model)
Young's Modulus (GPa)	20	A (MPa): 50
Poisson's Ratio	0.36	B (MPa): 101
Density (kg/m ³)	2100	$\dot{\epsilon}_0$ (s ⁻¹): 0.001
Thermal Conductivity (W/mK)	0.56	n: 0.08
Specific Heat (J/kgK)	1260	m: 0
		C: 0.03
		T_m (K): 1573
		T_0 (K): 293

Boundary conditions were applied to replicate the experimental setup (Figure 2.6). The base of the cylindrical bone specimen was clamped to mimic experimental constraints, while the top and lateral surfaces were left free to deform. The drill was subjected to rotational motion at 3,000 RPM and linear advancement with a feed rate of 0.004 m/s to simulate the drilling process. Contact interactions between the drill and the bone were modeled using a surface-to-surface contact formulation. A penalty method was used for normal contact enforcement, while tangential interactions were governed by Coulomb friction with a coefficient of 0.3, reflecting realistic experimental conditions.

Figure 2.6: *Boundary conditions applied to the bone specimen.*



The dynamic explicit analysis was performed using Abaqus/Explicit, which is well-suited for capturing transient and high-rate events such as drilling. Nonlinear geometric effects were included to account for the large deformations encountered during the drilling process. The time step was automatically controlled by the software using a stable time increment criterion, typically on the order of microseconds, to ensure numerical stability.

Figure 2.7: *Finite Element Model of the Bone-Dental Drill Assembly*



The computational effort for the simulation was significant, with a wallclock time of approximately 50,576 seconds (14 hours, 0 minutes, and 41 seconds). The user CPU time was recorded as 50,442 seconds, while the system time was 88.4 seconds, utilizing a 4-core parallel configuration on a standard workstation. These timings encompassed all phases of the analysis, including mesh generation, preprocessing, solution, and post-processing. The results obtained from the simulations were consistent with experimental observations, validating the modeling approach and the chosen parameters.

2.5.1 Thermal Modeling

To investigate the thermal effects during the drilling process, a coupled thermal-displacement modeling approach was employed. This advanced method allowed for the

simultaneous evaluation of mechanical deformation, heat generation, and temperature distribution within the workpiece, providing a comprehensive understanding of the interactions between these phenomena.

The finite element model utilized C3D8T elements, which are 8-node thermally coupled brick elements designed to capture both structural deformation and heat transfer processes. Each element accounted for trilinear displacement and temperature degrees of freedom, ensuring accurate simulation of the coupled behavior. The element mesh was refined near the drilling interface, where steep temperature gradients were anticipated. A mesh resolution of 0.5 mm was applied in these critical regions, consistent with the mechanical model, to ensure high fidelity in capturing thermal and mechanical responses.

Temperature-dependent material properties were incorporated into the model to accurately represent the thermal behavior of the bone. These properties included thermal conductivity, specific heat capacity, and density, which were integrated with the JC plasticity model to reflect the temperature-dependent mechanical behavior of biological tissues. The JC model was further augmented with thermal softening terms, enabling realistic simulation of material response under elevated temperatures. Heat conduction within the bone was modeled using Fourier's law, which governed the transfer of heat from the drilling site to surrounding regions. Convective heat loss to the environment was applied to the outer surfaces of the specimen, with a heat transfer coefficient representing air convection. The initial temperature of the system was set to ambient room conditions (25°C).

Frictional heat generation at the drill-bone interface was a critical aspect of the thermal model. A surface-to-surface contact interaction was implemented to simulate heat generation due to friction during drilling. The frictional heat flux was calculated based on the contact pressure, sliding velocity, and a friction coefficient of 0.3, consistent with experimental conditions. Approximately 90% of the frictional energy was assumed

to be converted into heat, a typical value for similar simulations. This heat flux boundary condition ensured realistic thermal energy distribution across the interface, enabling accurate prediction of temperature rise and Heat-Affected Zone (HAZ).

The simulation outputs provided detailed insights into the thermal and mechanical effects of drilling. Key results included the maximum temperature at the drill-bone interface, temperature gradients within the bone, and the extent and depth of the heat-affected zone. These outputs were essential for evaluating potential thermal damage to the biological tissue during the drilling process. Validation of the thermal model was performed using experimental data obtained from a K-type thermocouple, confirming the reliability of the simulation results.

The coupled thermal-displacement analysis required significant computational effort, with a wallclock time of approximately 50,576 seconds (16 hours, 48 minutes, and 52 seconds). This duration encompassed all stages of the simulation workflow, including mesh refinement, model setup, numerical solving, and result postprocessing. The analysis outcomes closely matched experimental observations, demonstrating the robustness of the modeling framework in capturing both thermal and mechanical interactions during the drilling process.

3. EXPERIMENTAL METHODS

The study of mechanical properties in drilling applications, particularly for both CD and UAD in implant contexts, is crucial for the biomedical community, including orthopedic surgeons and biomedical engineers. A primary objective of this research is to develop a finite element model that can accurately simulate the penetration force and temperature effects within the material under both CD and UAD conditions. This dual modeling approach enables a comparative analysis of material responses to traditional and vibration-assisted techniques.

FEM serves as a viable substitute for certain experimental procedures, which are often resource-intensive and carry health risks. Notably, there has been limited focus on quantifying the mechanical properties of implant-related materials to supply essential input for numerical models of drilling processes. While previous studies have largely concentrated on the mechanical and thermal properties of cortical bones, this research is specifically dedicated to simulating and validating drilling parameters for implant materials in both CD and UAD settings.

The FE model integrates experimental data on cutting force and temperature to validate simulation outcomes in both drilling modalities. This research program is designed to establish a comprehensive FE model that accurately reflects the material's mechanical response to CD and UAD, thereby enhancing the reliability and applicability of drilling simulations in biomedical applications.

3.1 Drilling Experiment

3.1.1 Specimen Preparation

The preparation of test specimens is a crucial aspect of ensuring experimental precision, reliability, and reproducibility. For this study, femur bones from sheep were selected as the test material due to their close anatomical and mechanical resemblance to

human cortical bone. To address the potential variability in tissue properties associated with post-mortem intervals, special care was taken to standardize the handling and timing of experiments. The preparation process, as illustrated in Figures 3.1, 3.2, 3.3, and 3.4, followed a rigorous protocol to ensure consistency across all specimens.

Figure 3.1: *Bone preparation procedure showing the initial selection and cleaning stages.*



The femur bones were sourced from an authorized biological supplier, with all specimens harvested within 48 hours post-mortem to mitigate alterations in their mechanical and structural properties resulting from ischemia and cellular degradation. This post-mortem timeframe was selected based on studies of ex vivo bone behavior, which demonstrate that tissue characteristics, particularly viscoelastic properties, undergo significant changes following the cessation of blood flow [84]. By adhering to this controlled harvesting interval, the mechanical properties of the specimens were preserved in a state

closely resembling their in vivo condition, thereby ensuring reliability and consistency during experimentation. Further research could build upon these findings by systematically examining the temporal progression of ex vivo bone property changes over extended durations.

Upon procurement, specimens underwent an initial cleaning phase to remove residual soft tissues, including muscle, tendons, and fat. As shown in Figure 3.2, surgical scalpels and forceps were used to ensure precision in cleaning while maintaining the structural integrity of the cortical bone. Subsequently, the specimens were rinsed thoroughly with sterile saline solution to remove debris and maintain hydration. Maintaining hydration during this stage was critical, as dehydration can adversely affect the mechanical properties of bone tissue, including its stiffness and fracture resistance.

Figure 3.2: *Cleaning of femur specimens to remove soft tissues and maintain hydration.*



The bones were then sectioned into uniform segments approximately 5 cm in length using a precision band saw, as illustrated in Figure 3.3. The mid-diaphyseal regions of the femurs were prioritized due to their consistent cortical thickness (approximately 3 mm) and uniform material properties. The sectioning process was performed with meticulous care to ensure clean and straight cuts, which facilitated accurate mounting during the experimental procedures.

Figure 3.3: *Bone cutting using a precision band saw, highlighting the uniform segment preparation.*

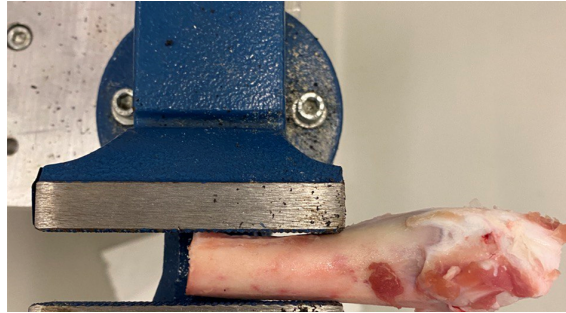


Figure 3.4: *Prepared bone specimens showcasing uniformity and readiness for experimentation.*



To standardize the drilling surface, the periosteum was carefully removed using surgical scalpels, revealing a clean cortical surface. Any remaining surface irregularities were addressed by gently polishing the bone with fine-grit sandpaper. This ensured a uniform interface between the drill bit and the bone, reducing variability during the drilling experiments and enhancing the reproducibility of results. The final prepared specimens, ready for experimentation, are shown in Figure 3.4.

To maintain the physiological and mechanical properties of the bone tissue during storage, all specimens were immediately wrapped in sterile saline-soaked gauze following preparation. Each specimen was then sealed in a polyethylene bag to retain moisture and stored at 4°C in a temperature-controlled refrigeration unit. This procedure helped mitigate dehydration and the subsequent degradation of mechanical properties. Although refrigeration effectively slows tissue deterioration, it is important to note that the viscoelastic properties of bone may still change over time, even under controlled storage conditions [84].

Prior to experimentation, each specimen underwent a detailed inspection to verify the absence of anomalies such as fractures, irregularities in cortical thickness, or defects that could compromise the validity of the results. Only specimens meeting the strict inclusion criteria of uniform cortical thickness (approximately 3 mm) and structural integrity were selected for testing. This meticulous inspection ensured that only high-quality specimens were used, thereby improving the reliability and validity of the experimental results.

By adhering to this rigorous preparation protocol and standardizing the post-mortem interval, as well as the storage and handling conditions, the study minimized variability and ensured the consistency of mechanical properties across specimens. This approach not only facilitated the reproducibility of the experiments but also provided a reliable foundation for analyzing the effects of drilling parameters on bone tissue under controlled conditions.

3.1.2 Equipment and Procedure

This section details the experimental setup and procedures employed to measure the thrust force and thermal effects during CD. The experiment was designed with precision instrumentation and a controlled setup to ensure reliable data collection for understanding the mechanical interactions and heat generation in CD.

3.1.2.1 Experimental Hardware

The primary drilling motion was achieved using a DKZM 15 linear module (Figure 3.5), which provided accurate linear movement at a rate of 5 mm per revolution. Mounted on a 120 mm $\times$ 150 mm plate, the module enabled controlled advancement along the drilling axis, allowing precise feed rate adjustments. A Nema 17 stepper motor, featuring 200 steps per revolution, was coupled to the module via a coupling connection. This motor setup, controlled via Arduino with an L298 driver, allowed for fine-tuned feed rate control as shown in Figure 3.6.

Figure 3.5: *Linear Module*

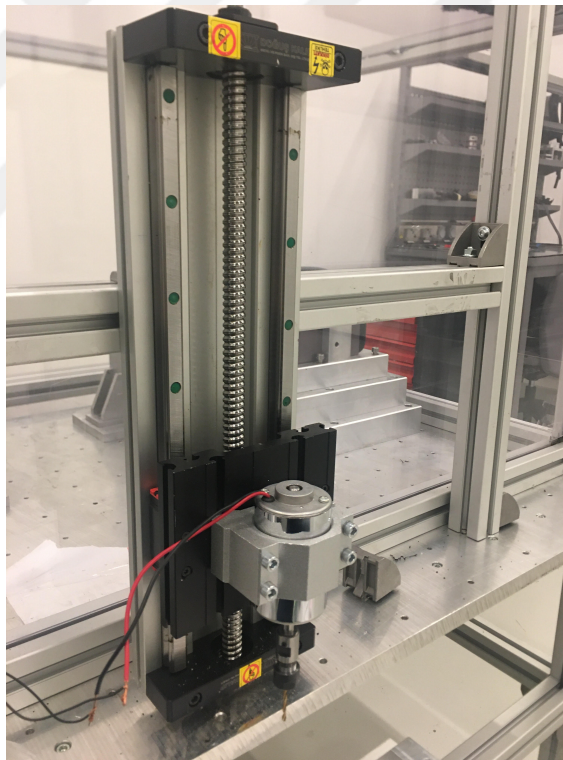
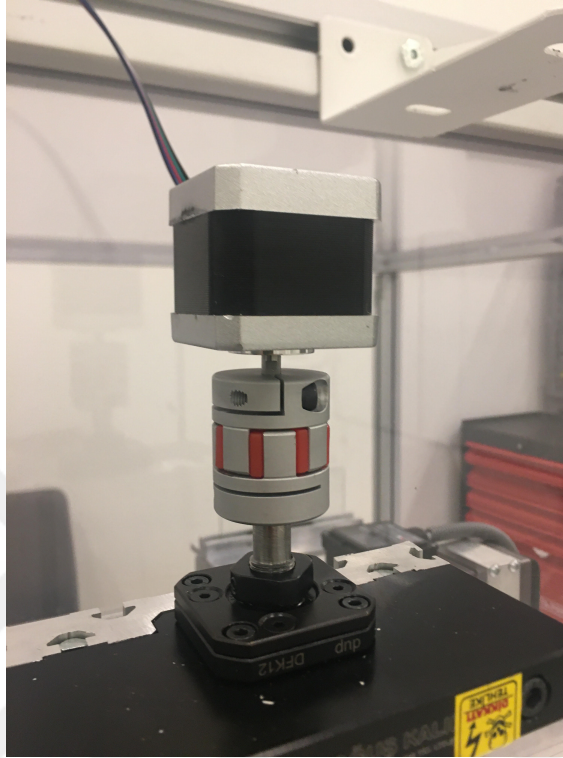
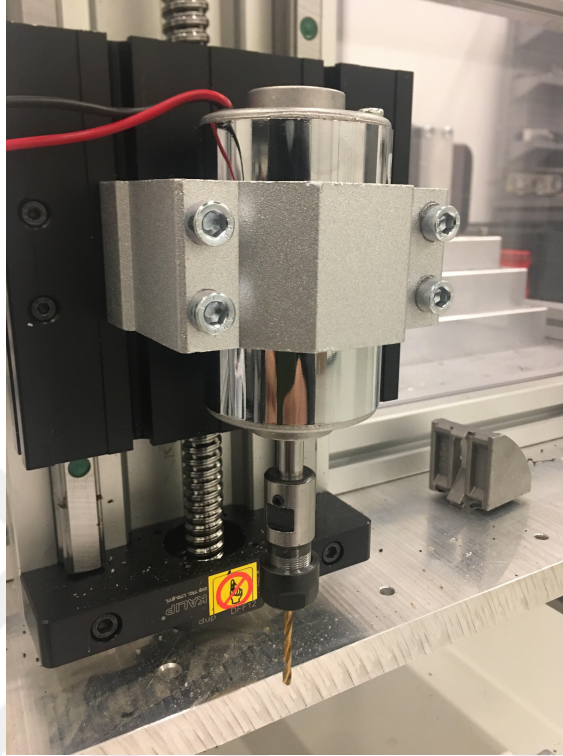


Figure 3.6: *Step Motor*



The rotational motion of the drill was driven by a DC motor (Figure 3.7) with an operating voltage range of 12–48 V, achieving a maximum speed of 3000 RPM at 12 V. The motor was securely mounted on a custom holder, which was attached to the linear module plate to ensure stability and minimize vibration. To enhance control, a voltage regulator was integrated into the system, allowing precise adjustment of the input voltage to the motor. This setup ensured consistent rotational speed, which was critical for evaluating drilling forces under steady-state conditions, providing reliable and repeatable results for the analysis.

Figure 3.7: *DC Motor*



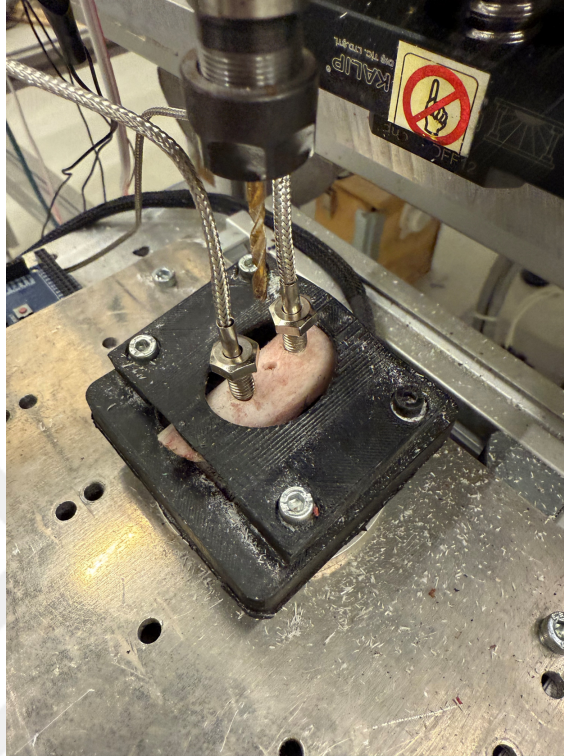
Force measurement was conducted using the OptoForce HEX Force/Torque Sensor (OnRobot A/S, Odense, Denmark), which provided precise, multi-axis measurement of the forces and torques generated during drilling (Figure 3.8). With its ability to measure in all three force directions (F_x , F_y , F_z) and three torque axes (T_x , T_y , T_z), the sensor enabled a comprehensive analysis of axial thrust force (F_z), rotational torque (T_z), and lateral forces that could indicate tool misalignment or material irregularities. The sensor's high resolution (250 mN for F_z and 1.11 mNm for T_z) was essential for the detailed mechanical analysis required in this study.

Figure 3.8: *Force Sensor*



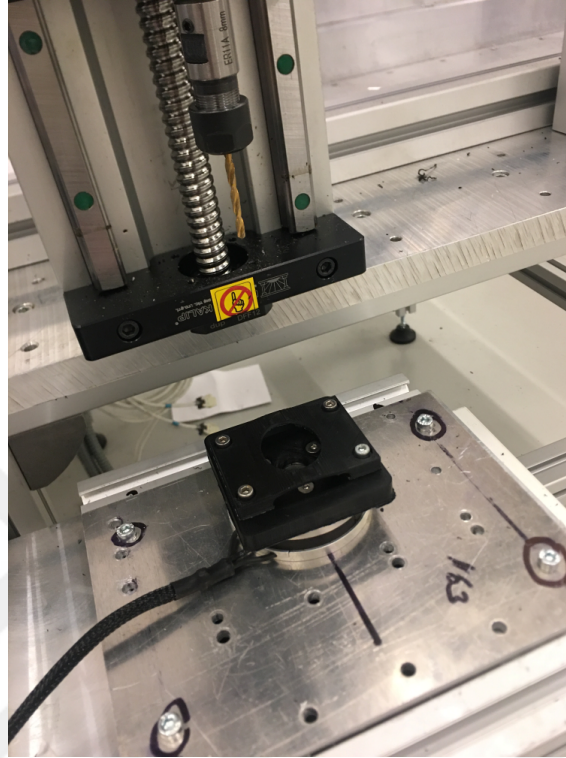
Thermal measurements were performed using a K-type thermocouple thermometer integrated with a MAX6675 sensor module. This setup monitored temperature variations at the drilling interface to provide precise observations of heat generation during drilling. The thermocouple, capable of measuring temperatures in the range of 0°C to 1024°C, was positioned close to the drilling site to ensure accurate capture of temperature fluctuations. The MAX6675 module, with its resolution of 0.25°C, facilitated reliable temperature readings, which were transmitted to an Arduino via the Serial Peripheral Interface (SPI) protocol and subsequently transferred to a PC for real-time acquisition and visualization. This setup provided critical insights into the thermal effects induced by friction and material deformation during drilling.

Figure 3.9: *K-type Thermometer*



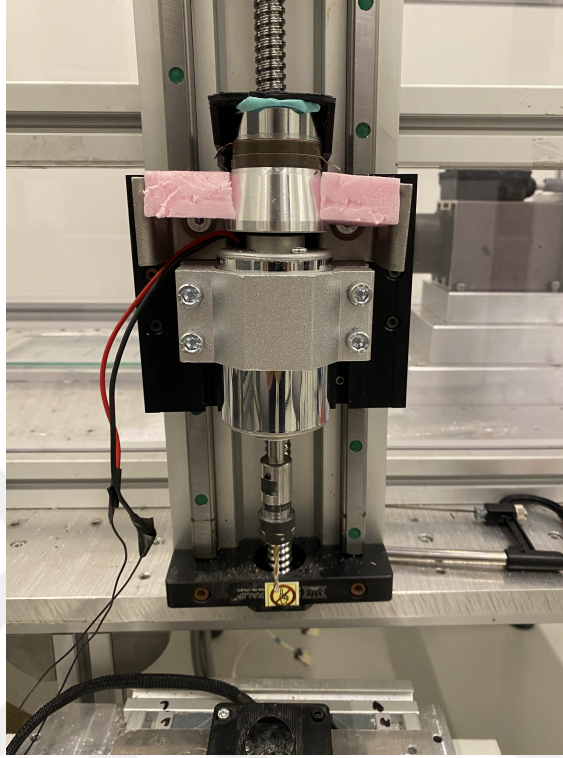
To ensure stable and precise data collection, the dynamometer and thermocouple were mounted using a combination of custom fixtures. This included a Sigma profile fixture for enhanced rigidity and a 3D-printed fixture designed specifically for specimen fixation. The 3D-printed fixture, fabricated from high-strength polymer using additive manufacturing, was optimized to securely hold the bone specimens without lateral or rotational movement. Recessed grooves cradled the specimens precisely during the experiment, as illustrated in Figure 3.10. The fixture was also designed to interface seamlessly with the force sensor, ensuring accurate force measurements while minimizing vibration artifacts and maintaining data integrity.

Figure 3.10: *Sensor Fixtures Used in the Experiment*



The ultrasonic transducer, adapted from an ultrasonic cleaner, operated at a frequency of 40 kHz with a vibration amplitude of 10 microns. Figure 3.11 highlights the alignment of the transducer with the drill bit and its configuration, including the connection to the booster, which ensured efficient energy transmission during the drilling process.

Figure 3.11: *Ultrasonic transducer*



3.1.2.2 Experimental Procedure

Prior to conducting the drilling trials, the dynamometer was calibrated to ensure accuracy in capturing thrust force (F_z). The calibration process involved applying known reference loads to validate the dynamometer's linear and reliable response, establishing a consistent baseline for subsequent experimental readings. The drilling experiments were then performed at room temperature without additional cooling to simulate ambient conditions. The drill bit, a 3 mm diameter tool held securely in an ER11 collet on an 8 mm shaft, was aligned perpendicularly to the workpiece surface to ensure uniform penetration and minimize variations in force and thermal measurements. Drilling parameters, including feed rate and rotational speed, were carefully set and maintained consistently

throughout each trial. The rotational motion of the drill was powered by a Direct current (DC) motor, while the feed rate was controlled via the stepper motor of the linear module.

During each trial, thrust force data were collected in real time through the dynamometer, with signals conditioned using charge amplifiers and recorded on a connected computer. Simultaneously, thermal data from the K-type thermocouple thermometer were logged at regular intervals to monitor temperature variations at the drilling interface. Each parameter set was repeated five times, and the data from these trials were averaged to produce representative values for thrust force and temperature. This repetition and averaging ensured that minor experimental variations were accounted for, providing a robust dataset for analysis.

Post-experiment, the collected data were analyzed to investigate the relationship between drilling parameters and the mechanical and thermal responses of the sample. The thrust force and thermal measurements were plotted and examined to identify patterns or trends associated with the selected drilling parameters. This comprehensive analysis provided critical insights into the forces and heat generated during CD, forming a foundation for deeper exploration of drilling dynamics.

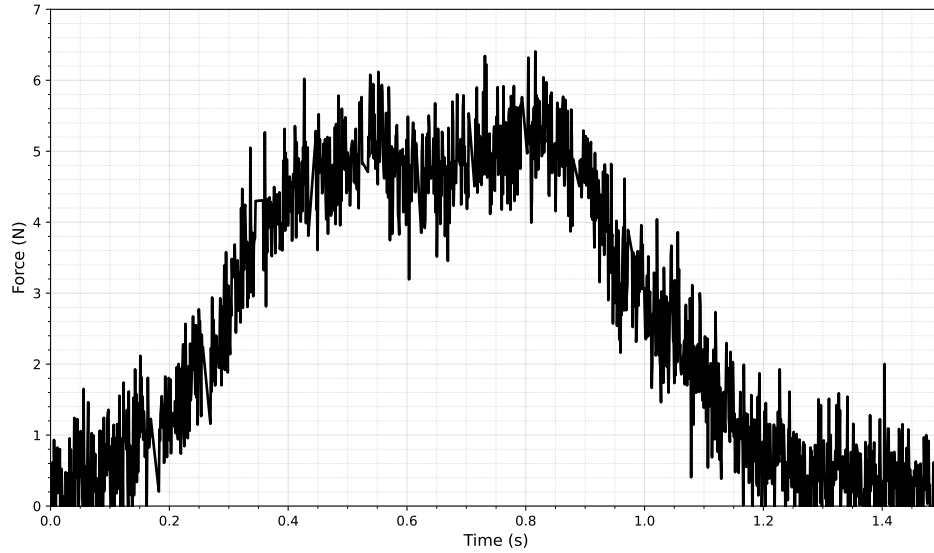
4. RESULTS AND DISCUSSIONS

Typical force-time curves obtained from the simulations for both CD and UAD are presented in this chapter. The results illustrate the distinct mechanical behavior associated with each technique, highlighting the dynamic force variations observed during the drilling process. The force profiles are analyzed to evaluate the impact of vibration on cutting efficiency, force reduction, and overall drilling performance. By comparing these results, the influence of vibration parameters on drilling mechanics is elucidated, providing critical insights into the advantages of UAD over CD methods.

4.1 Experimental results

The experiment aimed to analyze the force dynamics involved in a simulated drilling process, with a focus on capturing raw force data throughout the operation. The setup utilized a stepper motor integrated with a DKZM sliding module, operating at a controlled feed rate of 220 mm/min to ensure consistent linear motion during drilling. The rotational speed of the drill was adjusted to 3000 RPM through voltage regulation, maintaining the precision necessary for the study. A high-resolution Force sensor was incorporated into the assembly to monitor the real-time force variations, providing a direct measurement of the interaction forces. The raw data presented in Figure 4.1 depicts the time-dependent force response as the drill transitioned through the penetration phase and engaged with the outer surface of the bone. This synchronization of force measurements with the distinct phases of penetration and drilling provides crucial insights into the mechanical behavior of the material under operational conditions. The unprocessed nature of the data reflects the sensor's direct output, forming the basis for subsequent analysis and parameter optimization.

Figure 4.1: *Force Measurement at 3000 RPM*



The minor oscillations observed at the peak force values are ascribed to the high sensitivity of the measurement system and the dynamic interactions induced by the operational vibrations of the drilling apparatus.

4.1.0.1 Application of the Butterworth Filter in Data Processing

To ensure the reliability and precision of the recorded force-time data, the Butterworth low-pass filter was applied to mitigate the influence of high-frequency noise while preserving the integrity of the signal's critical features. The presence of high-frequency noise is common in data acquisition processes, especially when sensitive sensors or high-speed data logging systems are employed. The Butterworth filter was selected due to its characteristic of having a maximally flat magnitude response in the passband, which allows for the preservation of low-frequency signal components while effectively suppressing higher-frequency noise.

The Butterworth filter is mathematically described in Equation (4.1) by the following transfer function in the continuous domain :

$$H(s) = \frac{1}{\sqrt{1 + (s/\omega_c)^{2n}}} \quad (4.1)$$

where:

- s is the complex frequency variable in the Laplace domain,
- ω_c is the cutoff angular frequency, and
- n is the filter order, which controls the steepness of the roll-off.

For digital applications, the filter is represented in Equation (4.2):

$$H(z) = \frac{\sum_{k=0}^N b_k z^{-k}}{1 + \sum_{k=1}^N a_k z^{-k}} \quad (4.2)$$

where b_k and a_k are the filter coefficients determined by the filter design, and N is the order of the filter. These coefficients were computed using the `scipy.signal.butter` function and applied using `scipy.signal.filtfilt`, ensuring zero-phase distortion.

In this study, a second-order Butterworth filter (i.e., $n = 2$) was employed. The order of the filter determines the rate of attenuation in the stopband; for a second-order filter, this corresponds to a roll-off of 40 dB per decade beyond the cutoff frequency. The cutoff frequency was set to 50 Hz, chosen to effectively eliminate high-frequency noise without distorting the essential low-frequency components of the signal. The cutoff frequency is critical because it defines the boundary beyond which the filter attenuates the signal. The corresponding normalized cutoff frequency was calculated in Equation (4.3) based on the sampling rate:

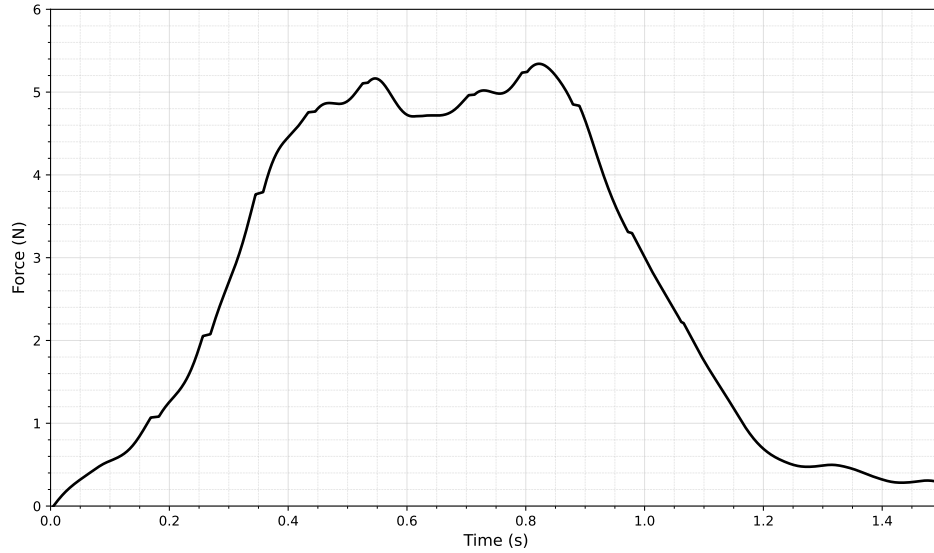
$$f_c = \frac{f_{\text{cutoff}}}{f_s/2} \quad (4.3)$$

where f_s is the sampling rate. In this research, the cutoff frequency of 50 Hz was chosen after careful spectral analysis of the raw data, ensuring that the noise was attenuated without affecting the key features of the force-time signal.

The frequency response of the Butterworth filter is characterized by a smooth, monotonic decrease in amplitude as the frequency increases beyond the cutoff frequency. This response is particularly advantageous as it avoids the ripples seen in other filters such as Chebyshev or Elliptic filters, which might distort the signal. The 50 Hz cutoff ensures that only the high-frequency noise components are attenuated, while the dynamics related to the drilling process are preserved in the filtered signal.

By applying the second-order Butterworth low-pass filter with a 50 Hz cutoff, the signal was effectively cleaned, removing high-frequency noise and ensuring that the critical transitions in the force-time data, which reflect the mechanical behavior during drilling, remained intact. This method not only improved the clarity of the signal but also contributed to the overall reliability of the data analysis, enabling a more accurate comparison between CD and UAD techniques.

Figure 4.2: *Filtered Force Measurement at 3000 RPM*



4.2 Simulation validation

The numerical simulations were designed to replicate the experimental drilling process, focusing on evaluating the force dynamics. A FEM was developed using Abaqus, with Python scripting employed to automate the setup, execution, and post-processing of the simulations. The drill was represented as a rigid body using R3D3 elements, and the bone-like workpiece was modeled with C3D8R elements. The material behavior of the workpiece was defined using the Johnson-Cook plasticity model to accurately simulate dynamic loading conditions.

Boundary conditions were applied to mirror the experimental setup. The base of the workpiece was fixed to emulate experimental constraints, while the drill was assigned a rotational speed of 3000 RPM and a feed rate of 0.004 m/s. Surface-to-surface contact with a friction coefficient of 0.3 was modeled at the interface between the drill and the workpiece.

The time step for the simulations was set to 10^{-6} s, ensuring accurate resolution of dynamic responses during the drilling process. This fine time step was consistently applied for both CD and UAD simulations to maintain uniform temporal resolution.

Simulation results indicate a distinct oscillation in the force response, particularly during the transition phases of penetration and continuous drilling. These oscillations highlight the sensitivity of the numerical model to changes in material interaction and contact dynamics at the drilling interface.

The data obtained from the numerical simulations were synchronized with the experimental phases of penetration and drilling. Python scripting, along with the Matplotlib library, was employed for post-processing and visualization of the results. Time-dependent force data were extracted, plotted, and analyzed to ensure alignment with experimental raw data Figure 4.3. The figure illustrates the raw numerical force data over time, directly reflecting the simulation output without any additional filtering or adjustments. This raw representation emphasizes the consistency between experimental and numerical results and highlights the model's capability to capture the mechanical behavior during the drilling process.

Figure 4.3: *Force Output from Simulation Model*

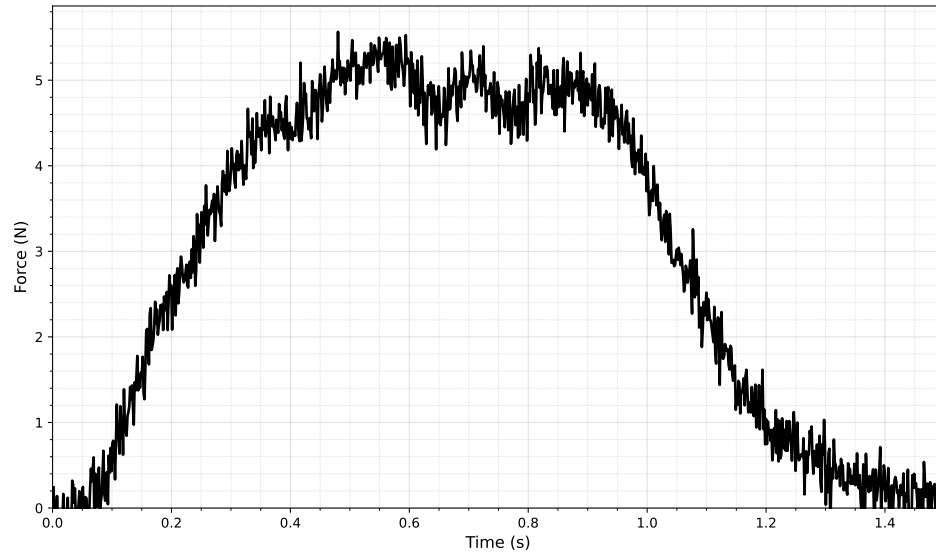
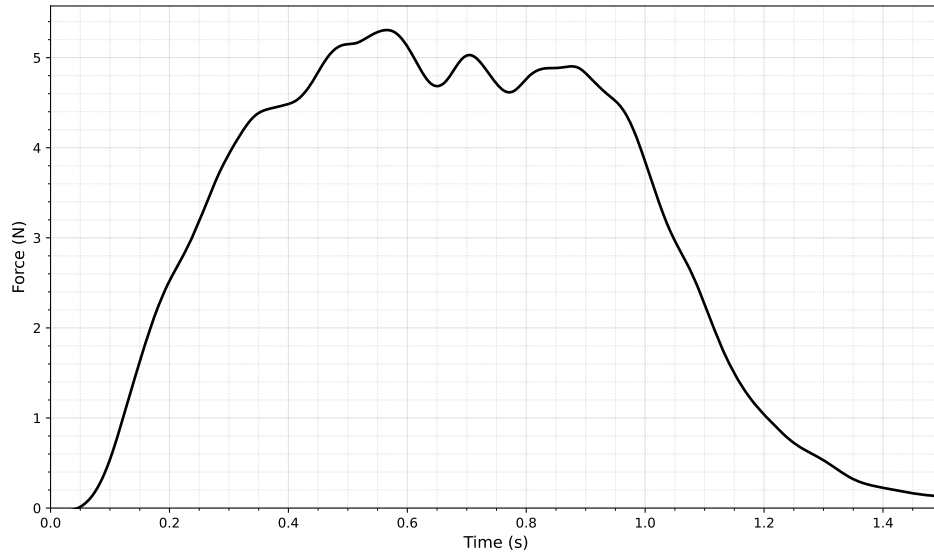


Figure 4.4 presents the numerical force data processed using a Butterworth low-pass filter, consistent with the approach applied to the experimental data. High-frequency noise was attenuated to retain the key dynamics of the force response during the penetration and drilling phases. This ensures improved clarity and facilitates a more accurate comparison between the numerical simulations and experimental results.

Figure 4.4: *Filtered Force Output from Simulation Model*



The validation of numerical models is a critical step in ensuring their applicability and reliability in replicating real-world phenomena. In this chapter, the numerical results obtained through simulations are systematically compared with experimental data to evaluate the model's predictive accuracy. This comparison is essential not only for verifying the underlying assumptions and boundary conditions of the numerical model but also for assessing its capability to capture the physical behavior of the system under investigation.

The evaluation is conducted using a suite of quantitative metrics, including Root Mean Square Error (RMSE), Mean Absolute Error (MAE), Mean Absolute Percentage Error (MAPE), Symmetric Mean Absolute Percentage Error (sMAPE), Maximum Difference (MD). These metrics provide a multi-faceted analysis of the model's performance, offering insights into both the overall and localized deviations between the numerical predictions and experimental observations.

The results presented in this chapter serve as a foundation for understanding the model's strengths and limitations. The discussion highlights areas where the numerical

approach accurately captures the experimental trends, as well as instances where discrepancies arise, shedding light on potential avenues for further refinement. By integrating these analyses, this chapter establishes a robust framework for evaluating the fidelity and applicability of the numerical model in addressing the research objectives.

4.3 Theoretical Background on Error Metrics

4.3.1 Root Mean Square Error

RMSE is a widely used metric for evaluating the accuracy of a numerical model by quantifying the standard deviation of residuals. RMSE is defined in Equation (4.4):

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n (y_i^{\text{obs}} - y_i^{\text{pred}})^2} \quad (4.4)$$

where y_i^{obs} represents the observed (experimental) value, y_i^{pred} is the predicted (numerical) value, and n is the number of data points. RMSE is particularly sensitive to large deviations, making it a valuable metric in scenarios where minimizing significant errors is critical.

4.3.2 Mean Absolute Error

MAE calculates the average magnitude of errors without considering their direction. It is expressed in Equation (4.5):

$$MAE = \frac{1}{n} \sum_{i=1}^n |y_i^{\text{obs}} - y_i^{\text{pred}}| \quad (4.5)$$

MAE is less sensitive to outliers compared to RMSE and provides an intuitive measure of the average prediction error, making it ideal for general accuracy assessments.

4.3.3 Mean Absolute Percentage Error

MAPE evaluates errors as a percentage of the observed values, offering a dimensionless and scalable measure. MAPE is defined in Equation (4.6):

$$MAPE = \frac{1}{n} \sum_{i=1}^n \left| \frac{y_i^{\text{obs}} - y_i^{\text{pred}}}{y_i^{\text{obs}}} \right| \times 100 \quad (4.6)$$

MAPE is particularly useful for comparing datasets with varying scales. However, it can become unreliable when observed values approach zero, leading to inflated percentages.

4.3.4 Symmetric Mean Absolute Percentage Error

sMAPE is a variation of MAPE that addresses its sensitivity to scale and division by zero issues. It is defined in Equation (4.7):

$$sMAPE = \frac{1}{n} \sum_{i=1}^n \frac{|y_i^{\text{obs}} - y_i^{\text{pred}}|}{\frac{|y_i^{\text{obs}}| + |y_i^{\text{pred}}|}{2}} \times 100 \quad (4.7)$$

sMAPE ensures a balanced evaluation by equally weighting over- and under-predictions, making it suitable for datasets with wide-ranging values.

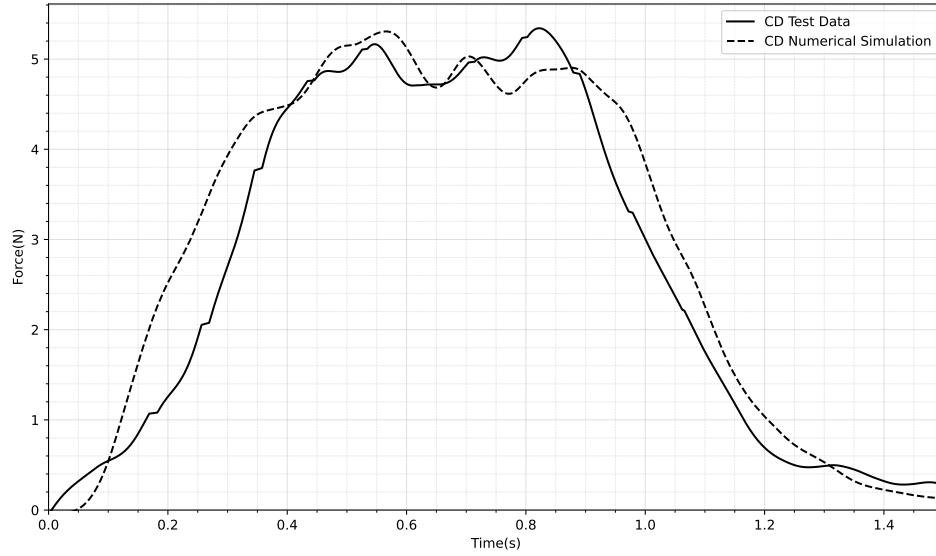
4.3.5 Maximum Difference

The MD metric identifies the largest deviation in Equation (4.8) between the observed and predicted values :

$$\text{Max Difference} = \max \left(|y_i^{\text{obs}} - y_i^{\text{pred}}| \right) \quad (4.8)$$

This metric highlights the worst-case scenario and is particularly relevant in applications where extreme deviations can have significant implications.

Figure 4.5: *Comparison of Force between Experimental Data and Simulation Model*



4.4 Validation of Simulation Model

The comparison between the numerical and experimental results was conducted using a range of statistical error metrics, including RMSE, MAE, MAPE, sMAPE, and MD. These metrics provide a comprehensive evaluation of the accuracy and reliability of the numerical model in replicating experimental observations. The analysis focuses on the data within the range of 0.4 to 0.9 seconds, where the primary behavior of the system is observed.(Table 4.1)

Table 4.1: *Numerical vs Experimental Comparison Metrics in CD*

Metric	Value	Percentage of Mean Experimental Value	Description
RMSE	0.2546	5.16%	Average deviation from experimental data
MAE	0.2014	4.08%	Average magnitude of errors
MAPE	-	4.09%	Errors as a percentage of observed values
sMAPE	-	4.05%	Uniform error distribution
Max Diff	0.5164	10.47%	Largest deviation observed

For the specified range, the RMSE value was calculated as 0.2546, which indicates that, on average, the numerical model's predictions deviate from the experimental

data by this amount. When expressed as a percentage of the mean value of the experimental dataset, the RMSE accounts for approximately 5.16%, which is indicative of high predictive accuracy. The MAE for the same range was computed as 0.2014, representing the average magnitude of the errors without considering their direction. When normalized by the mean value of the experimental data, the MAE constitutes approximately 4.08%. This low percentage further corroborates the numerical model's ability to provide reliable predictions with minimal average deviation from the experimental results.

The MAPE, which quantifies errors as a percentage of the observed values, was found to be 4.09%. This value reflects the relative accuracy of the numerical model and demonstrates its capacity to maintain consistency across varying magnitudes within the dataset. The low MAPE value is particularly significant as it provides a dimensionless measure of error, enabling comparisons across datasets or experiments with different scales. Similarly, the sMAPE was calculated as 4.05%, which closely aligns with the MAPE value, indicating a uniform distribution of errors across the dataset. The use of sMAPE mitigates the potential influence of extreme values or near-zero data points, ensuring a balanced assessment of model performance. This consistency between MAPE and sMAPE suggests that the numerical model does not disproportionately over- or under-predict the experimental values.

The maximum deviation between the numerical and experimental data within the specified range was recorded as 0.5164. When expressed as a percentage of the mean value of the experimental dataset, this deviation constitutes 10.47%. Although this value is higher than the average errors captured by RMSE and MAE, it represents the worst-case scenario rather than the typical behavior of the model. Such deviations are often localized and may result from specific conditions or transient phenomena that are challenging to capture in simulations.

The results indicate that the numerical model demonstrates a high degree of accuracy in replicating the experimental data, as evidenced by the low RMSE, MAE, MAPE, and sMAPE values. The RMSE, at 5.16% of the mean, highlights the model's ability to minimize overall deviations, while the MAE and MAPE, at approximately 4.08% and 4.09% respectively, underscore the precision of the model in terms of both magnitude and proportionality. The slightly higher MD, at 10.47%, suggests that isolated discrepancies exist, potentially due to high-frequency noise, transient events, or limitations in the modeling of specific dynamics. Such deviations warrant further investigation into the localized behavior of the model, particularly in regions of rapid change or high sensitivity. Overall, the combination of low average error metrics and acceptable maximum deviations supports the robustness and reliability of the numerical model. These results provide confidence in its applicability for analyzing the system's behavior and predicting outcomes under similar conditions.

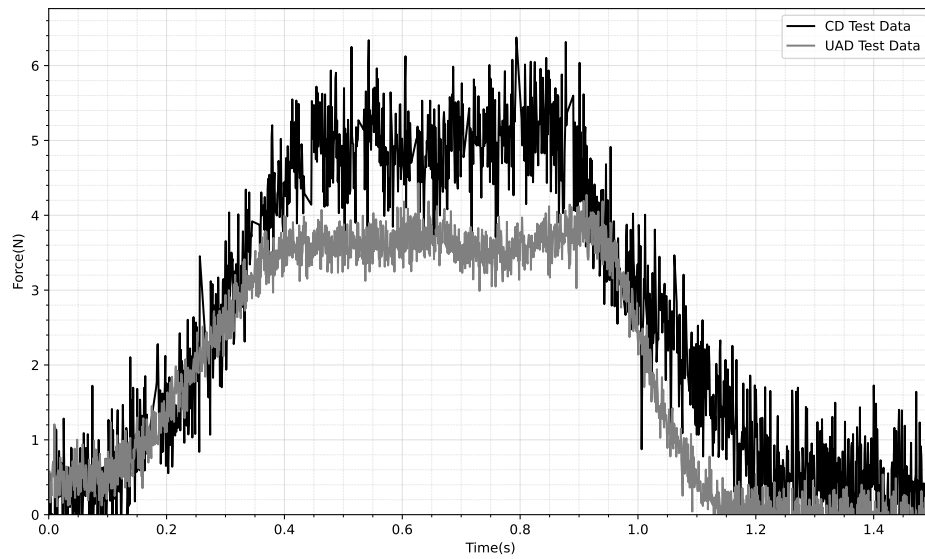
4.5 Force Dynamics in Ultrasonic-Assisted Drilling

UAD introduces high-frequency vibrations into the drilling process to enhance efficiency and reduce force requirements. In the UAD experiments conducted, a 40 kHz ultrasonic transducer was used to generate these vibrations, modulating the interaction between the drill bit and the bone surface. The force data obtained during the experiments displayed distinct oscillations, indicative of the high-frequency cyclic loading imparted by the ultrasonic vibrations. However, these oscillations were accompanied by noise, likely originating from experimental and environmental factors, as well as the inherent characteristics of the high-frequency transducer assembly.

The raw data, as shown in Figure 4.6, highlights the dynamic behavior of the force response during penetration and drilling phases. The observed noise superimposed on the oscillatory signal underscores the complexity of the interaction between the drill and the

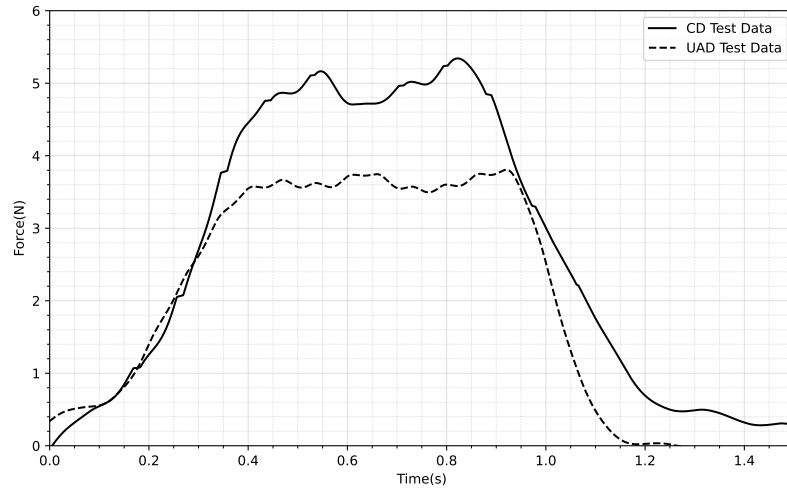
material under ultrasonic excitation. This raw dataset provides critical insights into the mechanical performance of the UAD process and serves as a foundational reference for further analysis, including filtering and comparisons with numerical simulations.

Figure 4.6: *Comparison of Raw Force Measurement between CD and UAD Experiments*



The filtered force data, processed to reduce noise and enhance the clarity of the oscillatory behavior observed during the UAD experiments, is illustrated in Figure 4.7.

Figure 4.7: *Comparison of Filtered Force Measurement between CD and UAD Experiments*



The filtered force data demonstrates an approximate 30% reduction in force for UAD compared to CD. This significant difference underscores the impact of high-frequency vibrations in reducing resistance during the drilling process. The comparison highlights the effectiveness of UAD in modulating the mechanical interaction between the drill and the material, providing clear evidence of its advantages over conventional methods.

To accurately simulate the UAD process, Abaqus was employed in conjunction with custom-developed user subroutines written in Fortran. These subroutines were utilized to superimpose a sinusoidal vibration at 40 kHz, with an amplitude of 10 micrometers, onto the linear constant velocity of 0.004 m/s. This implementation enabled precise modeling of the high-frequency oscillatory motion characteristic of UAD. Python scripting was further employed to integrate the subroutine functionalities with the overall simulation workflow, automating tasks such as setup, execution, and data processing. The simulations were conducted with a time step of 10^{-6} s, ensuring accurate resolution of

the dynamic responses and seamless synchronization between the numerical methods and experimental parameters.

Figure 4.8: *Validation of Raw Force Results between Experiment and Simulation Model for UAD*

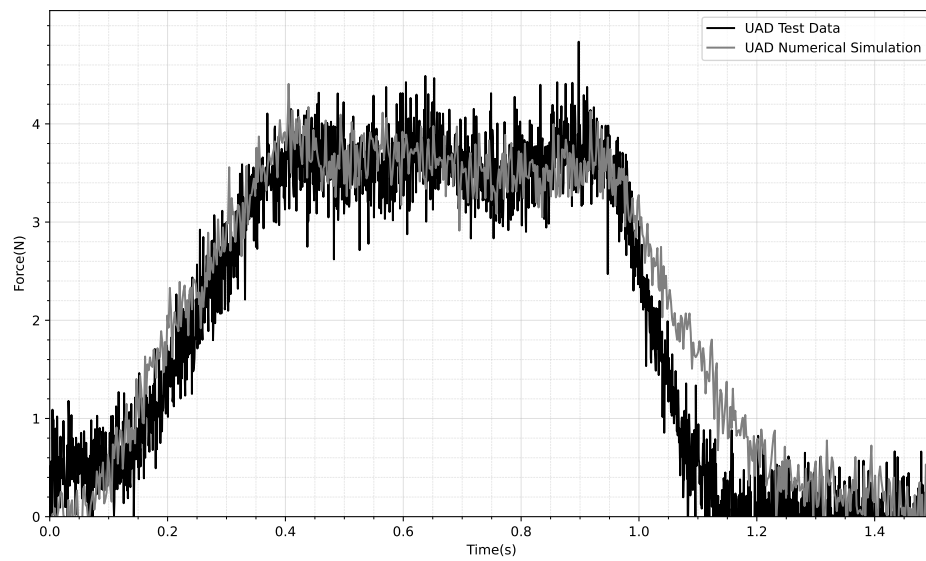


Figure 4.9: *Validation of Filtered Force Results between Experiment and Simulation Model for UAD*

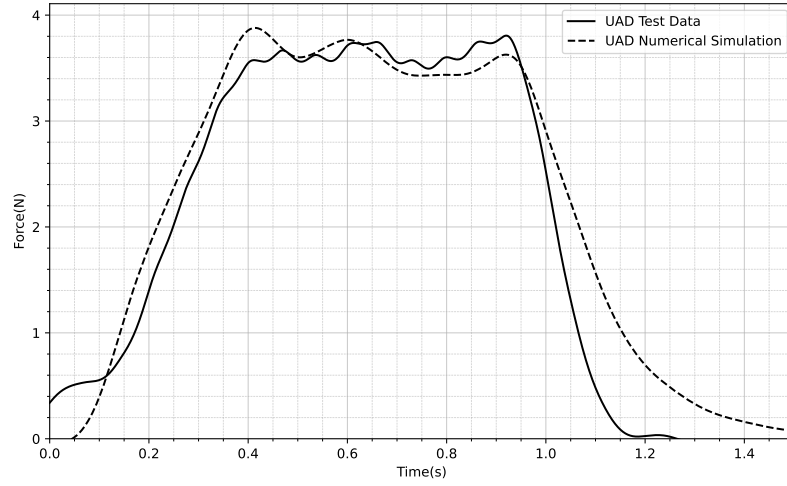


Figure 4.8 illustrates the validation results obtained from the numerical simulations and experimental data in their raw form, where high-frequency noise and oscillations are evident. Conversely, Figure 4.9 presents the filtered validation results, where a Butterworth low-pass filter has been applied to reduce noise and enhance the clarity of the force response. The comparison between these figures highlights the importance of filtering for improving data quality and facilitating more accurate analysis.

The accuracy of the numerical model in replicating the experimental results for UAD was evaluated using various error metrics. RMSE for the specified range was calculated as 0.1467, representing the average deviation between the numerical predictions and the experimental observations. This value corresponds to approximately 4.05% of the mean value of the experimental dataset within the defined range, highlighting the model's high predictive accuracy in capturing the overall behavior of the system.

Complementary to this, the Mean Absolute Error (MAE) was determined to be

0.1208, which reflects the average magnitude of the deviations, regardless of their direction. When normalized by the mean experimental value, the MAE constitutes approximately 3.33%, further underscoring the reliability of the model in providing accurate predictions with minimal deviation.

Additionally, the Mean Absolute Percentage Error (MAPE) was found to be 3.35%, quantifying the model's accuracy relative to the observed experimental values. This low percentage demonstrates the model's consistency across varying magnitudes of force data. The Symmetric Mean Absolute Percentage Error (sMAPE) was calculated as 3.34%, closely aligning with the MAPE value. The similarity between these metrics confirms that errors are uniformly distributed across the dataset, mitigating the influence of extreme values or near-zero data points, and ensuring a robust and unbiased assessment of model performance.

The maximum deviation observed between the numerical and experimental data within the specified range was 0.3065, which constitutes 8.46% of the mean experimental value. While this maximum difference is higher than the average errors reported by RMSE and MAE, it represents isolated occurrences rather than the typical behavior of the model. Such localized deviations are often attributed to transient phenomena or specific conditions that are challenging to fully replicate in numerical simulations. Nevertheless, the overall error metrics validate the numerical model's ability to reliably predict the force dynamics observed in UAD.

Table 4.2: *Numerical vs Experimental Comparison Metrics in UAD*

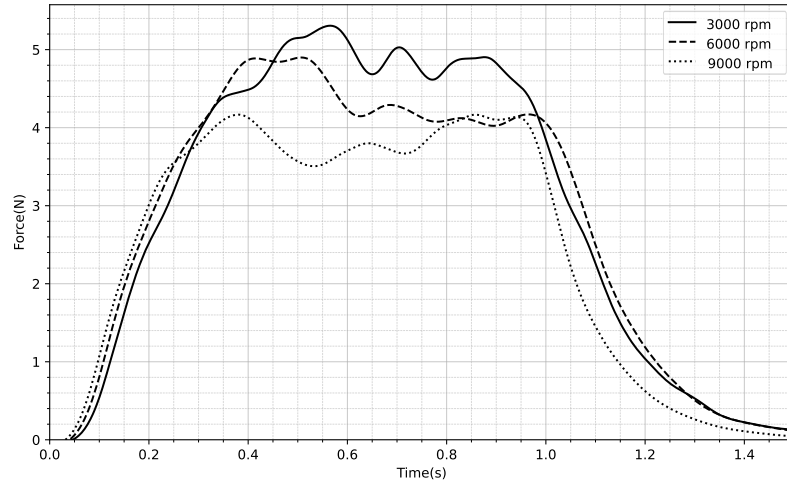
Metric	Value	Percentage of Mean Experimental Value	Description
RMSE	0.1467	4.05%	Average deviation from experimental data
MAE	0.1208	3.33%	Average magnitude of errors
MAPE	-	3.35%	Errors as a percentage of observed values
sMAPE	-	3.34%	Uniform error distribution
Max Diff	0.3065	8.46%	Largest deviation observed

4.6 Sensitivity Analysis

Sensitivity analysis was conducted to evaluate the influence of key parameters on the numerical model's accuracy and performance. This analysis provides insights into how variations in input parameters, such as material properties, contact conditions, and boundary settings, affect the force dynamics during drilling. The outcomes of this analysis enable the identification of critical factors and their impact on the reliability of the model, guiding parameter optimization for improved predictive accuracy.

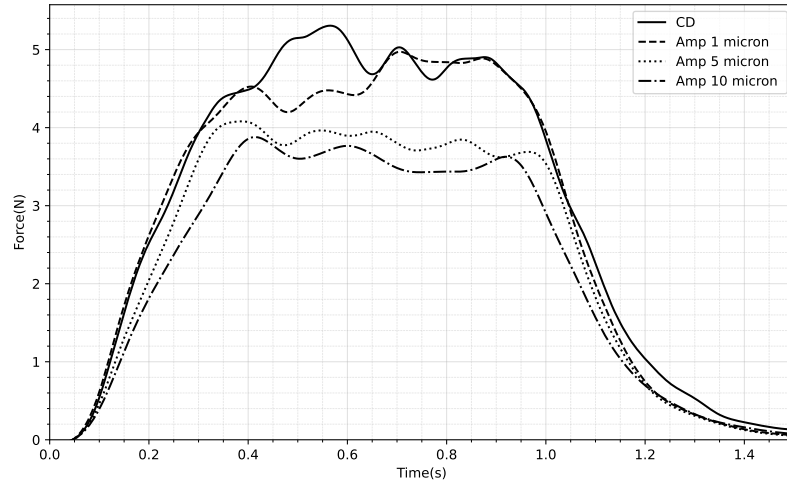
In particular, the rotational velocity of the drill, the frequency of ultrasonic vibrations, and the amplitude of the UAD were examined as critical parameters. Variations in the rotational velocity were observed to influence the overall force magnitude and drilling efficiency, while changes in frequency and amplitude directly affected the oscillatory behavior of the force response. These parameters play a pivotal role in determining the interaction dynamics between the drill and the material, and their optimization is essential for achieving the desired reduction in force and improving drilling performance. The sensitivity analysis results underscore the importance of precise control over these parameters to ensure consistency and reliability in both experimental and numerical simulations.

Figure 4.10: *Effect of Rotational Speed on Force*



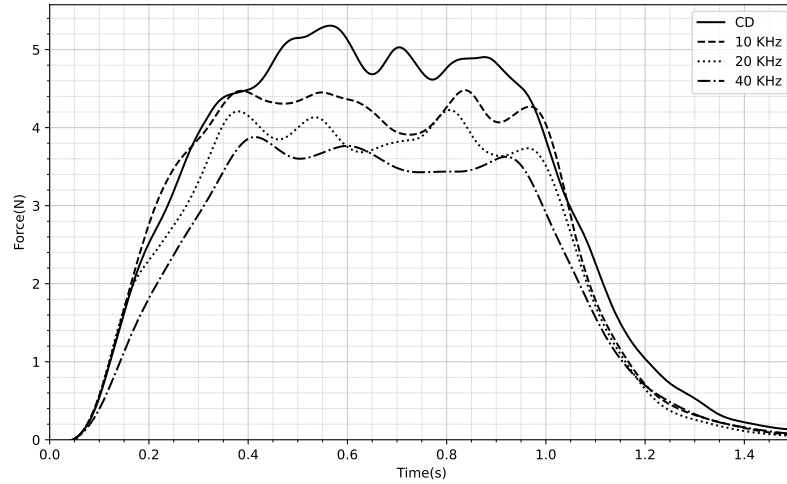
The influence of rotational velocity on the reduction of drilling force was also analyzed through numerical simulations. As shown in Figure 4.10, the base rotational velocity for both the experimental and numerical models was set to 3000 RPM. Increasing the rotational velocity to 6000 RPM resulted in a force reduction of 12.54%, while further increasing the velocity to 9000 RPM led to a substantial reduction of 25.12%. These results highlight the significant role of rotational velocity in improving the efficiency of the drilling process. The progressive reduction in force with increasing rotational velocity demonstrates its effectiveness in minimizing resistance and optimizing material removal. This analysis underscores the importance of fine-tuning rotational velocity, alongside vibration parameters, to achieve the best performance in UAD.

Figure 4.11: *Effect of Vibration Amplitude on Force*



The numerical simulations were further conducted to investigate the effect of varying amplitudes on the reduction of drilling force at a constant ultrasonic vibration frequency of 40 kHz. As shown in Figure 4.11, increasing the amplitude led to progressively greater reductions in drilling force. An amplitude of 1 micron resulted in a force reduction of 7.78%, indicating a modest improvement in efficiency. Increasing the amplitude to 5 microns achieved a significant reduction of 24.05%, while the highest amplitude of 10 microns led to the most substantial reduction of 30.34%. These results emphasize the critical influence of amplitude in enhancing the performance of UAD. The observed trend demonstrates the importance of optimizing both amplitude and frequency parameters to minimize mechanical resistance and improve drilling efficiency.

Figure 4.12: *Effect of Vibration Frequency on Force*

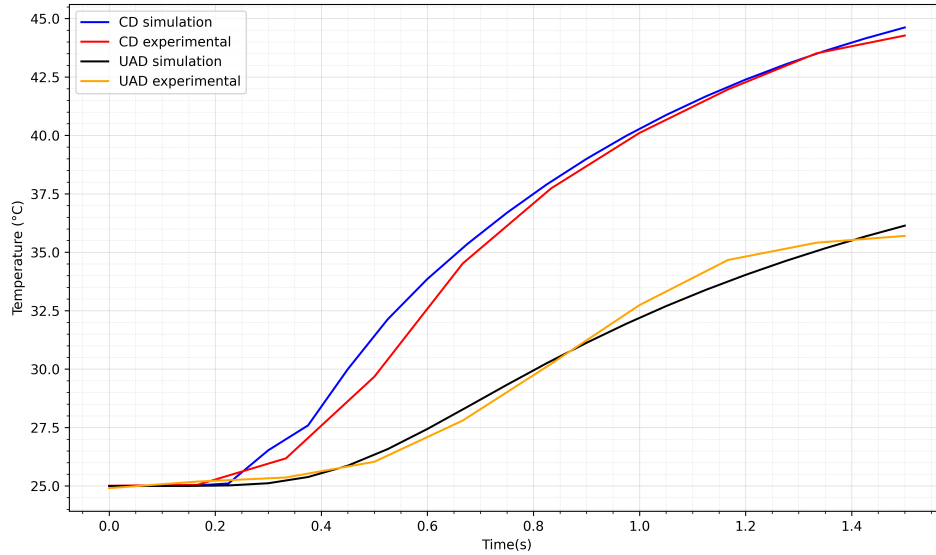


The numerical simulations were conducted to evaluate the effect of ultrasonic vibration frequency on the reduction of drilling force. By implementing an amplitude of 10 microns and varying the frequency, the results demonstrated a significant reduction in force compared to CD. As shown in Figure 4.12, a frequency of 10 kHz resulted in a force reduction of 14.48%, indicating a modest improvement in drilling efficiency. Increasing the frequency to 20 kHz led to a more pronounced force reduction of 22.44%, while the most substantial improvement was observed at 40 kHz, where the force reduction reached 30.34%. These results highlight the critical role of ultrasonic vibration frequency in enhancing the performance of UAD. The progressive reduction in force with increasing frequency underscores the importance of optimizing vibration parameters to achieve maximum efficiency and minimize mechanical resistance during the drilling process.

4.7 Thermal Effect Of UAD

Both CD and UAD begin the process at an approximately equal initial temperature of 25°C. As drilling progresses, their thermal profiles diverge significantly. CD is characterized by a rapid rise in temperature shortly after the 0.2-second mark, continuing to escalate sharply and reaching a peak value of approximately 45°C at 1.5 seconds. In contrast, UAD exhibits a more moderate and controlled temperature increase, culminating in a lower peak of around 35°C. This notable reduction in thermal accumulation during UAD can be attributed to the high-frequency vibratory motion, which improves chip evacuation, reduces frictional contact at the cutting interface, and minimizes the conversion of mechanical work into heat. Such thermal behavior is particularly advantageous when machining temperature-sensitive materials, where elevated temperatures may lead to microstructural degradation or functional impairment. Figure 4.13 presents the temperature evolution for both drilling methods, clearly demonstrating the thermal benefits of UAD over CD. These findings underscore the suitability of UAD for applications demanding precise thermal control and minimal thermal damage during drilling.

Figure 4.13: *Comparison of Temperature between Experimental Data and Simulation Model*



The comparison of temperatures generated during CD and UAD highlights the thermal efficiency of the UAD process. In the case of CD, the experimental temperature reached 45.25°C, while the simulated temperature was 44.62°C, indicating a very small difference of 0.63°C. For UAD, the experimental temperature was recorded as 35.75°C, and the simulated temperature was 36.14°C, with a difference of only 0.39°C. These results show a strong agreement between experimental observations and numerical simulations. Moreover, UAD resulted in a considerable reduction in temperature when compared to CD. Specifically, the experimental results showed a temperature decrease of 9.5°C, corresponding to a 21.0% reduction, while the simulation results indicated a decrease of 8.48°C, or 19.0%. This notable reduction is likely due to the influence of ultrasonic vibrations, which help to reduce friction and enhance heat dissipation during the drilling process. The close correlation between the experimental and simulated data confirms the reliability of the numerical model in accurately representing the thermal behavior of both

drilling techniques.

4.8 Response Surface Modeling and Optimization

RSM is a collection of statistical and mathematical techniques used to explore and optimize processes influenced by multiple variables. It was first introduced by Box and Wilson in 1951 and later formalized in engineering applications by Myers, Montgomery, and Anderson-Cook [85, 86]. RSM is particularly effective when multiple input variables affect critical output responses, especially when those relationships are nonlinear and interactional. A typical RSM framework uses designed experiments—often full-factorial or central composite designs—to fit a second-order polynomial model. This approach allows for response prediction across the design space and facilitates multi-objective optimization [86].

In biomedical contexts, particularly bone drilling, RSM has been successfully applied to minimize thermal damage and mechanical loading through process parameter tuning. Tahmasbi et al. [87] used RSM to optimize temperature and drilling force in robotic cortical bone drilling. Similarly, Rosidi et al. [88] combined finite element simulations with the Taguchi method to identify safe drilling parameter ranges that reduce thermal necrosis.

In the present study, RSM was implemented to capture the relationship between drilling parameters and critical performance metrics. A full-factorial simulation matrix comprising 27 combinations ($3 \times 3 \times 3$) of input parameters—rotational speed (3000–9000 rpm), vibration frequency (10–40 kHz), and amplitude (1–10 μm)—was constructed. The outputs were the peak temperature and Root Mean Square (RMS) of thrust force, both extracted from validated FEM simulations. The details of the simulation matrix are presented in Table 4.3.

The simulation data were used to construct second-order polynomial regression

Table 4.3: Full-factorial design matrix: simulation results for temperature and RMS force under varying process parameters.

Speed (rpm)	Vibration Frequency (kHz)	Amplitude (μm)	Temperature (°C)	RMS Force (N)
3000	10	1	42.8	3.1
3000	10	5	44.7	3.1
3000	10	10	40.3	3.1
3000	20	1	42.7	3.0
3000	20	5	40.3	3.0
3000	20	10	41.2	2.9
3000	40	1	42.9	3.0
3000	40	5	41.9	3.0
3000	40	10	39.2	2.9
6000	10	1	49.5	3.1
6000	10	5	46.4	3.0
6000	10	10	46.4	2.9
6000	20	1	49.1	3.0
6000	20	5	46.5	2.9
6000	20	10	39.1	2.8
6000	40	1	48.9	2.9
6000	40	5	42.1	2.8
6000	40	10	40.6	2.7
9000	10	1	46.7	2.6
9000	10	5	40.8	2.6
9000	10	10	39.3	2.3
9000	20	1	46.3	2.5
9000	20	5	45.2	2.5
9000	20	10	38.1	2.2
9000	40	1	44.7	2.5
9000	40	5	46.0	2.2
9000	40	10	45.9	2.2

models using Python's PolynomialFeatures and LinearRegression functions.

The general structure of the model is referred in Equation (4.9):

$$y = \beta_0 + \sum \beta_i x_i + \sum \beta_{ii} x_i^2 + \sum \beta_{ij} x_i x_j \quad (4.9)$$

where y is the predicted output (temperature or force), x_i are the input parameters, and the β terms are the regression coefficients. These models enabled estimation of both main effects and interactions among the drilling parameters. In this study, x_1 , x_2 , and x_3 denote rotational speed, vibration frequency, and vibration amplitude, respectively. RSM model coefficients for temperature and force are shown in Table 4.4.

Table 4.4: *RSM model coefficients for temperature and force*

Coefficient	Temperature	Force
β_0	41.128931	2.256257
β_1	0.698921	−0.186236
β_2	−0.343509	−0.050687
β_3	−1.804548	−0.060194
β_4	−1.610370	−0.098053
β_5	0.685313	−0.006420
β_6	−0.339032	−0.027023
β_7	0.541564	0.015755
β_8	0.210707	0.003582
β_9	0.033839	−0.010794

The sensitivity indices plotted in Figure 4.14 and Figure 4.15 were derived directly from the fitted RSM coefficients as follows: all non-intercept regression coefficients β_i were first converted to their absolute values. Each term's individual contribution was then normalized by the total sum to compute its raw percentage influence according to the Equation (4.10):

$$p_i = 100 \times \frac{|\beta_i|}{\sum |\beta_i|} \quad (4.10)$$

Ensuring that $\sum p_i = 100\%$. For interaction terms (e.g., β_{12} , representing the interaction between speed and frequency), the computed percentage was equally distributed between the two corresponding parameters. The total contribution of each input factor—rotational speed, vibration frequency, and amplitude—was then obtained by aggregating its own linear and quadratic terms along with its half-shares of all relevant interaction effects. A final rounding adjustment was applied to ensure that the resulting sensitivity indices summed exactly to 100%. These results are illustrated in Figure 4.14 for the temperature response and in Figure 4.15 for the force response.

Figure 4.14: *Sensitivity of Temperature to parameters.*

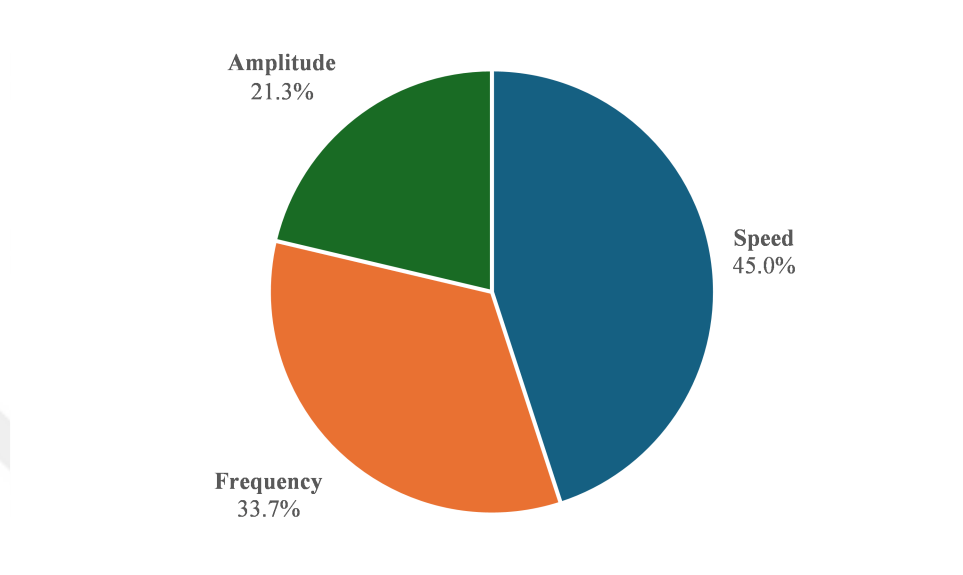
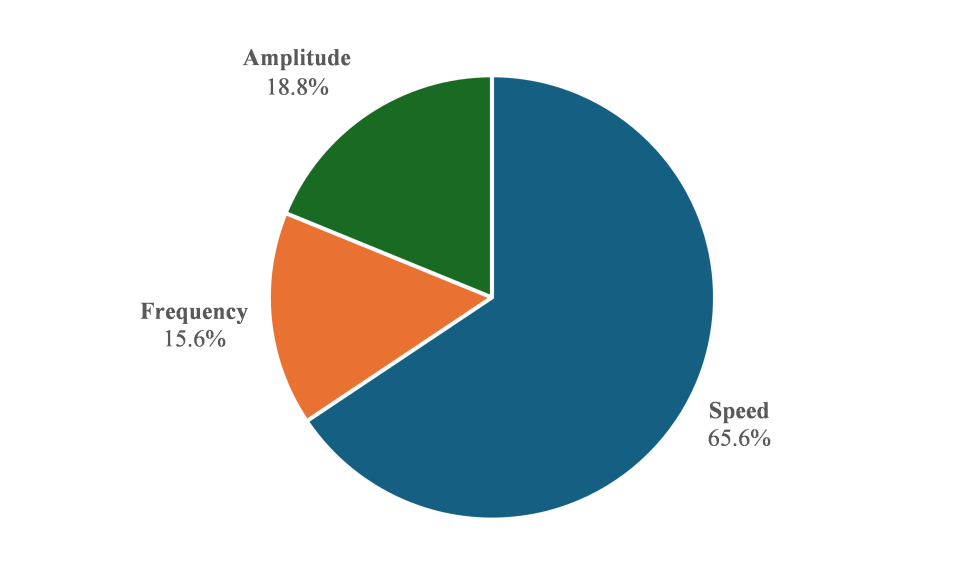


Figure 4.15: *Sensitivity of Force to parameters.*



A weighted-sum multi-objective optimization approach was utilized to determine

the optimal combination of drilling parameters that minimize both the thermal and mechanical responses during ultrasonic-assisted bone drilling. The optimization was carried out using a gradient-based local search algorithm, specifically the L-BFGS-B (Limited-memory Broyden–Fletcher–Goldfarb–Shanno with Box constraints) method, which is well-suited for problems involving smooth, differentiable objective functions with bound constraints.

The scalar objective function was formulated in Equation (4.11) as a weighted sum of the predicted peak nodal temperature and the RMS thrust force, both derived from second-order response surface models:

$$\text{Objective}(\mathbf{x}) = w_T \cdot T(\mathbf{x}) + w_F \cdot F(\mathbf{x}) \quad (4.11)$$

where $T(\mathbf{x})$ and $F(\mathbf{x})$ are the predicted temperature and force from the RSM models, and w_T , w_F are the corresponding weighting factors. In this study, both thermal and force responses were assigned equal importance using normalized weights of 1:1 to ensure a balanced trade-off between thermal and mechanical objectives.

The L-BFGS-B algorithm is a gradient-based quasi-Newton method that approximates the inverse Hessian matrix using limited memory, making it computationally efficient for medium-scale problems with smooth, continuous cost functions. The method supports simple box constraints, allowing the optimization to be performed within the defined practical limits of rotational speed (3000–9000 rpm), vibration frequency (10–40 kHz), and amplitude (1–10 μm).

Due to the convex and smooth nature of the fitted response surfaces, the optimizer exhibited rapid and stable convergence, typically requiring only a limited number of iterations to reach a solution. The resulting optimal configuration reflects a compromise between minimizing thermal damage and reducing mechanical load, thereby contributing to safer and more effective drilling outcomes in biomedical applications.

Figure 4.16 and Figure 4.17 present the response surface visualizations derived from the second-order polynomial regression models fitted to the full-factorial simulation dataset. These figures illustrate the predicted effects of ultrasonic vibration frequency (kHz) and amplitude (μm) on the two output variables—peak nodal temperature and RMS thrust force—at three discrete rotational speeds: 3000 rpm, 6000 rpm, and 9000 rpm. Each colored surface corresponds to a fixed rotational speed and represents the model's continuous prediction across the frequency–amplitude design space. Specifically, Figure 4.16 displays the temperature surface in degrees Celsius ($^{\circ}\text{C}$) on the z -axis, while Figure 4.17 presents the force surface in Newtons (N). The visual comparison of these surfaces reveals the nonlinear and coupled influence of input parameters, thereby supporting the selection of optimal process conditions in subsequent multi-objective optimization.

Figure 4.16: *Predicted RMS thrust force across three spindle speeds.*

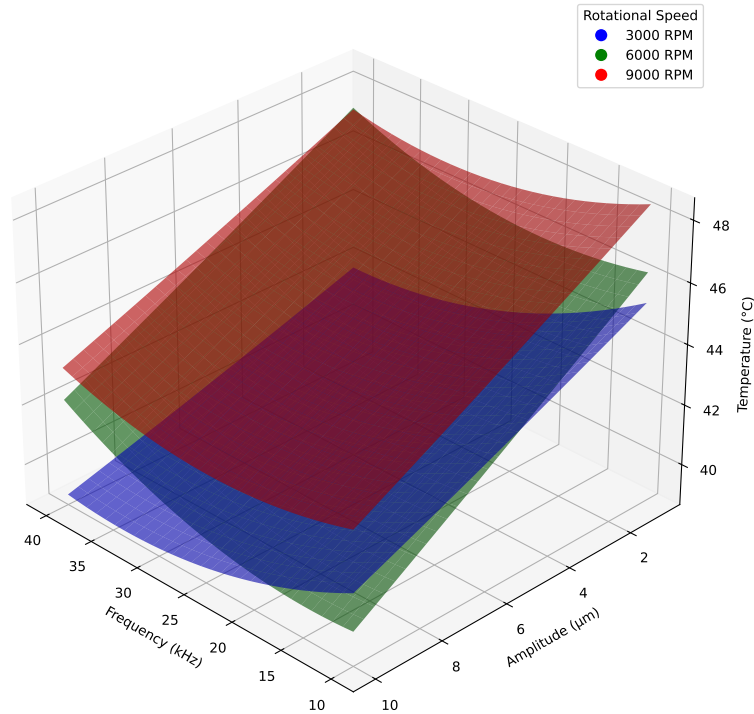
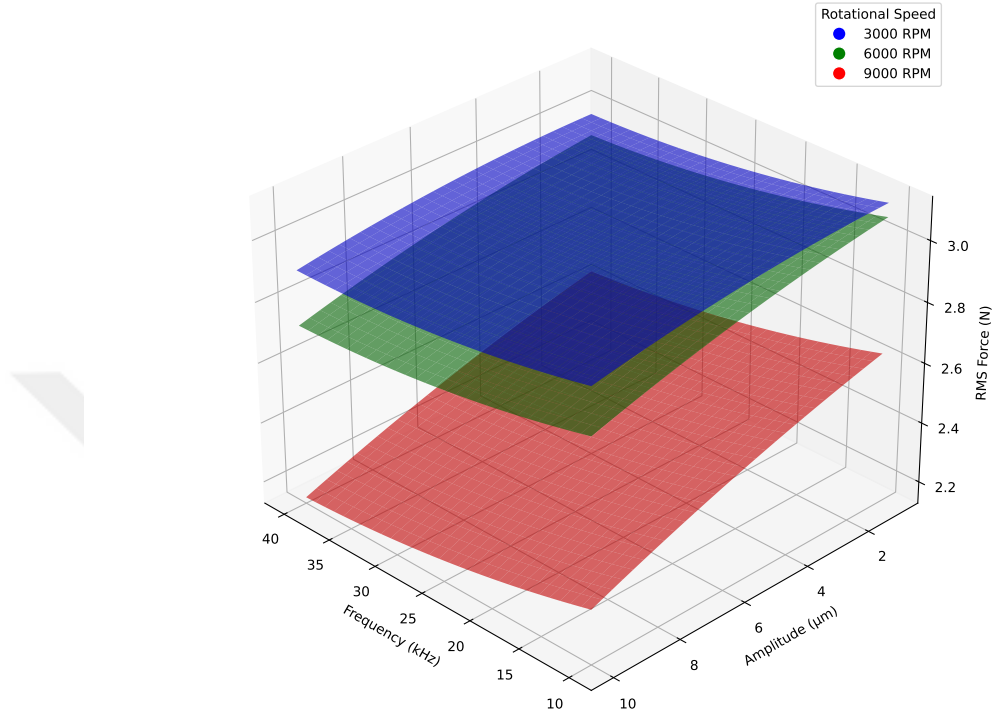


Figure 4.17: *Predicted temperature surfaces across three spindle speeds.*



Among the evaluated combinations, the response surface-based optimization identified an optimal drilling condition of 5499 rpm rotational speed, 34.50 kHz ultrasonic frequency, and 13.07 μm amplitude when equal importance was assigned to minimizing both thrust force and temperature. This compromise solution offers a balanced trade-off between mechanical efficiency and thermal safety, making it well-suited for drilling in thermally sensitive biological tissues.

When the objective was weighted more heavily toward force minimization, the optimization process yielded a parameter set of 9000 rpm, 41.81 kHz, and 17.53 μm , emphasizing maximum cutting efficiency by reducing thrust force, albeit with an increased

thermal load. In contrast, when thermal performance was prioritized, the optimum configuration shifted to 4252 rpm, 24.89 kHz, and 12.28 μm , favoring reduced heat generation and improved thermal control, while allowing for a moderately increased mechanical load.

These results demonstrate the ability of the weighted-sum multi-objective optimization framework to adapt the process parameters according to specific clinical or operational requirements, allowing for customized drilling strategies that prioritize either mechanical performance or thermal safety depending on the application context.

4.9 Discussion

This study provides a detailed evaluation of UAD as an advanced method in dental implantology, highlighting its significant advantages over CD. By combining FEAs with experimental analyses, the research demonstrates that UAD effectively reduces thrust forces and thermal effects, improving bone preservation and potentially enhancing clinical outcomes. However, applying these findings to real-world clinical settings requires careful consideration of the study's limitations and broader implications.

The *ex vivo* experimental setup used in this study was essential for accurately measuring the mechanical and thermal responses of bone tissue under controlled conditions. The results show that UAD reduces thrust forces by 30–35% and peak temperatures by 25–30%, demonstrating its efficiency in minimizing mechanical and thermal stresses. These controlled experiments provided valuable insights into the effects of vibration frequency, amplitude, and rotational speed. However, the *ex vivo* nature of the study means that important *in vivo* factors, such as blood flow, nerve responses, and the body's natural healing processes, were not included. For instance, in a living body, blood flow may help dissipate heat more effectively, potentially altering the thermal patterns observed in the lab. Similarly, tissue responses such as inflammation and remodeling could affect the

healing process and integration of the implant.

Another key limitation is the use of uniform bone specimens, which may not represent the wide variation in bone quality and structure seen in patients. Factors such as age, bone density, and medical conditions like osteoporosis can influence how bone responds to UAD. For example, weaker, osteoporotic bone may require specific adjustments to the vibration parameters to achieve the desired outcomes. Addressing these patient-specific differences through clinical studies and computational modeling will be crucial for making UAD applicable to a broader range of scenarios.

Despite these challenges, this study shows that UAD has great potential to improve dental implant procedures. By lowering mechanical and thermal stresses, UAD reduces the risks of complications such as bone microdamage and thermal necrosis. These improvements are expected to lead to faster healing times and better implant stability, making UAD a valuable alternative to CD.

Beyond dental applications, the principles of UAD may also be applied to other areas requiring precise bone drilling, such as orthopedic or craniofacial surgeries. However, widespread use in clinical practice may be limited by the cost of ultrasonic equipment and the need for specialized training. Collaborative efforts between researchers, clinicians, and manufacturers will be necessary to overcome these challenges and integrate UAD into routine surgical workflows.

In conclusion, this study provides strong evidence of UAD's advantages over CD, but further research is needed to confirm its effectiveness in real-world conditions. Future studies should include *in vivo* experiments and account for variations in patient characteristics to fully validate the clinical relevance of UAD. By addressing these gaps, this research contributes to the development of safer, more effective, and patient-focused solutions in dental and medical surgeries.

5. CONCLUSION

This study comprehensively investigated the mechanical and thermal behavior of CD and UAD through experimental and numerical approaches. The results highlight the advantages of UAD in improving drilling performance, reducing mechanical resistance, and minimizing thermal effects, thereby validating its effectiveness as a superior alternative to conventional methods. In addition, the work is distinguished by the development of a validated finite element framework, enabling predictive control over process parameters to ensure thermal and mechanical safety in drilling operations.

5.1 Mechanical Performance

The force dynamics during drilling revealed significant reductions in forces with the application of ultrasonic vibrations. Numerical simulations demonstrated that increasing the vibration frequency progressively reduced the drilling force. At 10 kHz, the force reduction was 14.48%, increasing to 22.44% at 20 kHz, and achieving a maximum reduction of 30.34% at 40 kHz, with a fixed amplitude of 10 μm . Similarly, varying the amplitude at a constant frequency of 40 kHz resulted in reductions of 7.78% at 1 μm , 24.05% at 5 μm , and 30.34% at 10 μm . These results emphasize the importance of optimizing both vibration frequency and amplitude to maximize the efficiency of the UAD process. Furthermore, sensitivity analysis revealed that increasing rotational velocity also contributed to a decrease in drilling force, with reductions of 12.54% at 6000 rpm and 25.12% at 9000 rpm compared to the baseline of 3000 rpm. These findings underscore the critical role of vibrational parameters and rotational speed in minimizing mechanical resistance and enhancing material removal efficiency.

5.2 Thermal Performance

The thermal analysis demonstrated the superior heat management capabilities of UAD compared to CD. For CD, the experimental temperature peaked at 45.25°C, while the UAD process reduced this to 35.75°C, representing a 21.0% reduction. Numerical simulations closely aligned with these experimental findings, with the CD temperature recorded as 44.62°C and the UAD temperature as 36.14°C, corresponding to a 19.0% reduction. The improved thermal performance of UAD is attributed to intermittent tool-bone contact, reduced friction, and improved chip evacuation under ultrasonic vibrations, all of which contribute to enhanced heat dissipation.

5.3 Validation of Numerical Models

The validation of numerical simulations against experimental data demonstrated strong agreement across all performance metrics. Quantitative evaluations using error metrics such as RMSE, MAE, and MAPE confirmed the model's accuracy. The RMSE was 0.1467 (or 4.05% of the mean value), while the MAE and MAPE were 0.1208 (3.33%) and 3.35%, respectively. These low error values highlight the reliability of the finite element model in capturing the dynamic behavior of the drilling process. The strong alignment between simulation and experimental results confirms the robustness of the numerical framework and its potential for predictive modeling and process planning.

5.4 Implications for Ultrasonic-Assisted Drilling

The findings of this study emphasize the transformative potential of UAD in enhancing drilling performance. The significant reductions in force and temperature achieved through ultrasonic vibrations demonstrate its ability to improve operational efficiency while minimizing thermal damage and mechanical load. These benefits are particularly critical in applications involving heat-sensitive materials, such as cortical bone.

Additionally, sensitivity analysis and the implementation of a RSM provided a foundation for multi-objective optimization of process parameters. The optimal configuration identified through RSM—5499 rpm spindle speed, 34.50 kHz vibration frequency, and 13.07 μm amplitude—represents a balanced trade-off between thermal and mechanical performance. The study thus establishes a validated and generalizable framework for optimizing UAD parameters, with future potential in microscale manufacturing, clinical surgery, and aerospace drilling applications.

5.5 Future Directions

While this study validates the effectiveness of UAD through experimental and numerical analyses, further research should address additional factors such as drill geometry, material anisotropy, and the application of multi-frequency vibrations. Coupled thermal-mechanical numerical models could provide deeper insights into the interplay between force dynamics and heat generation. Moreover, exploring UAD's use in diverse industrial and biomedical contexts would broaden its applicability and effectiveness.

Integrating Artificial Intelligence (AI) into UAD research could significantly improve process efficiency and precision. AI algorithms, such as machine learning, can optimize parameters like vibration frequency and feed rate, adapting them to specific materials and conditions. Real-time AI monitoring systems could detect anomalies, such as excessive forces or temperatures, and adjust parameters dynamically to ensure consistent performance. Additionally, AI models can complement finite element simulations by offering data-driven insights and material-specific optimizations. Advanced applications, including predictive modeling for tool wear and virtual experimentation, could enable intelligent and autonomous UAD systems. Incorporating AI into UAD research has the potential to revolutionize the field, enhancing reliability and expanding its applications across industrial and biomedical domains.

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APPENDICES

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