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Advances in Nitinol Laser Cutting: Exploring Mixed Gas Applications and Process Optimization

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Abstract*: Nitinol, a shape memory alloy widely used in biomedical and aerospace industries, requires precise fabrication techniques such as laser cutting to maintain its unique properties. Mixed gas environments have demonstrated potential in enhancing the efficiency and quality of laser cutting processes, but their role remains insufficiently explored. This review investigates advancements in Nitinol laser cutting, focusing on mixed gas applications and process optimization through bibliometric analysis of studies till 2025. Key trends highlight the growing use of reactive gases for improved energy absorption and inert gases for superior surface quality, but challenges persist in standardizing methodologies and addressing scalability. Unanswered questions include the environmental impact of gas mixtures and their effects on long-term material performance. Recommendations emphasize integrating real-time monitoring, machine learning, and sustainable gas technologies for future research.*

Keywords: Nitinol, Laser Cutting, Mixed Gas Applications, Process Optimization, Shape Memory Alloys, Reactive and Inert Gases, Thermal Effects, Surface Quality, Microstructural Integrity, Advanced Manufacturing Techniques

I. INTRODUCTION

Nitinol, a nickel-titanium alloy, is renowned for its unique properties, including shape memory effect (SME), superelasticity, and biocompatibility, making it indispensable in medical, aerospace, and robotics applications. When heated, its SME enables it to "remember" and return to its previous shape, and superelasticity permits considerable elastic deformation without causing irreversible harm. Because of its protective titanium oxide layer, nitinol is biocompatible and resistant to corrosion, making it suitable for use in implants and medical devices like stents and surgical instruments. Processing is difficult due of its intricate phase change behavior and work-hardening nature, necessitating exacting methods like laser cutting to preserve its remarkable qualities and functioning.

A. Laser Cutting's Significance in Nitinol Processing

As it can achieve high precision and preserve the material's special qualities, like shape memory and superelasticity, laser cutting has become the preferred method for processing nitinol. In contrast to traditional machining techniques, laser cutting provides a contactless technology that reduces processing-related mechanical stresses and distortion. For the intricate geometries needed in biomedical devices like stents and surgical instruments, this approach is especially well-suited. Furthermore, laser cutting guarantees constant quality, smooth edges, and tight tolerances—all of which are essential for applications where surface integrity has a significant impact on Nitinol's performance[1],[2].

However, there are still issues with laser cutting nitinol. The development of a heat-affected zone (HAZ), where localized heating can change the microstructure and jeopardize mechanical characteristics, is one significant problem. While dross production—solidified droplets of molten material—may deteriorate surface quality and dimensional precision, oxidation during the process might result in the creation of unwanted surface layers. To overcome these obstacles, laser parameters and assist gas compositions must be optimized to guarantee little heat damage and high-quality cuts[2].

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B. Assist Gases' Function in Laser Cutting

In laser cutting nitinol, assist gases are essential because they affect heat control, surface quality, and process efficiency. The material is protected from oxidation by inert gases such as argon, which guarantees clean cuts, no heat damage, and biocompatibility—all of which are essential for medical applications. Argon also lessens the heat-affected zone (HAZ) and produces a smooth surface finish. But when compared to reactive gases, it cuts more slowly. Cutting speed and surface quality are balanced in mixed gas settings, which combine reactive and inert gases to reduce oxidation and heat damage. The cut quality and the maintenance of Nitinol's special qualities, such superelasticity and shape memory, are directly impacted by the assist gas selection.

C. The review's objectives

With an emphasis on reactive, inert, and mixed gas conditions, this paper attempts to investigate the function of assist gases in enhancing Nitinol laser cutting. In order to provide efficient optimization techniques, it addresses issues including heat-affected zones, oxidation, and dross production while examining their implications on cut quality, thermal effects, and process efficiency.

D. The review's objectives

The choice of assist gases, such as compressed air, nitrogen, and oxygen, is crucial in laser cutting operations since it affects the cut's quality and efficiency. These gases have several purposes, including influencing the thermal dynamics during cutting, preventing oxidation, and expelling molten material from the cut zone. The presence of dross or slag, kerf breadth, and edge smoothness are all directly impacted by the assist gas selection. Oxygen, for example, can speed up cutting through exothermic reactions, but it can also cause oxidation, which lowers surface quality. Nitrogen, on the other hand, produces inert cutting conditions that result in cleaner edges free of oxidation, but they may also demand greater gas pressures and slow down cutting. Reduce the quality of the edge in comparison to pure gases. es.

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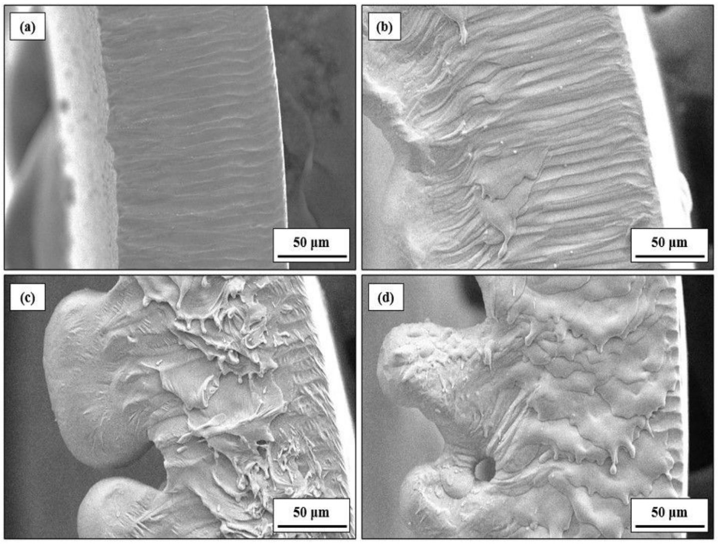

Figure 1. SEM images of Nitinol laser-cut edges using different assist gases: (a) Oxygen, (b) Argon, (c) Nitrogen, (d) Helium. These images illustrate the differences in cut edge morphology and their implications for material performance. Adapted from Otto et al. (2024) with permission under the Creative Commons Attribution 4.0 International License (DOI: https://doi.org/10.21203/rs.3.rs-4288707/v1)

This figure illustrates how different assist gases influence the cut edge morphology of Nitinol during laser cutting. Oxygen enhances cutting speed but induces oxidation, Argon maintains surface smoothness with slower cutting rates, Nitrogen prevents oxidation but may require higher gas pressure, and Helium minimizes thermal effects while preserving edge integrity.

II. MATERIAL CHARACTERISTICS AND PROCESSING DIFFICULTIES FOR NITINOL

Nitinol is crucial for medical and aeronautical applications because of its special qualities, which include shape memory effect, superelasticity, and biocompatibility[1],[2]. Its work-hardening nature and phase transformation behavior, however, present processing difficulties such as heat-affected zones, surface oxidation, and dross formation, necessitating the use of precise machining processes such laser cutting[1][2].

A. Nitinol's Material Properties

The nickel-titanium alloy nitinol has special qualities like superelasticity and shape memory effect (SME), which are essential for cutting-edge applications. Superelasticity, which is controlled by phase transitions between martensite and austenite, permits considerable elastic deformation without irreversible damage, whereas SME allows Nitinol to return to its former shape when heated.

Because of its protective titanium oxide (TiO2) layer, which offers exceptional corrosion resistance, nitinol is biocompatible and appropriate for use in surgical instruments and medical equipment such as stents. Furthermore, it is perfect for applications needing flexibility and durability, such as cardiovascular implants and aircraft actuators, due to its excellent fatigue resistance and recoverable elongation.

B. Processing Difficulties

Dealing with nitinol poses many difficulties due to its intricate phase change behavior and extreme sensitivity to mechanical and thermal conditions. Heat-affected zones (HAZ) can change the microstructure during machining, affecting superelasticity and the shape memory effect. While surface roughness and dross production jeopardize dimensional accuracy, oxidation during processing might result in undesired surface properties. Traditional procedures are made more difficult by nitinol's low machinability and work-hardening tendency, which necessitate precise techniques like laser cutting. Furthermore, to preserve its special qualities for biomedical and aeronautical applications, it is essential to keep a consistent composition and reduce impurities.

III. MATERIAL CHARACTERISTICS AND PROCESSING DIFFICULTIES FOR NITINOL

Nitinol processing has been completely transformed by laser cutting, which provides an accurate, frictionless way to create complex shapes while maintaining its special qualities. The goal of recent developments in laser cutting technology has been to increase the effectiveness and quality of cuts. Ultrafast and short-pulse lasers reduce heat-affected zones (HAZ), minimizing microstructural damage and maintaining the superelasticity and shape memory effect of nitinol[2],[5].

In order to maximize melt flow dynamics and reduce oxidation, the function of assist gases, such as oxygen and argon, has been thoroughly investigated. While inert gases like argon improve surface quality by lowering oxidation, reactive gases like oxygen speed up cutting through exothermic reactions[2],[3]. The advantages of both are further combined in mixed gas settings, which balance cut quality

A. Role of Assist Gases in Laser Cutting

Assist gases play a crucial role in Nitinol laser cutting by influencing cutting speed, surface quality, and thermal effects. Reactive gases, such as oxygen, promote exothermic reactions, enhancing cutting efficiency and speed, though they may cause surface oxidation[2],[6]. Inert gases like argon and nitrogen prevent oxidation, producing smoother surfaces but slower cutting speeds[3],[6]. Mixed gas environments combine these benefits, offering balanced solutions for precision and speed[5],[6],[7]. The choice of assist gas directly impacts the material’s biocompatibility and

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microstructural integrity, making its optimization critical for applications in high-precision fields like medical devices and aerospace components[6],[7],[4]

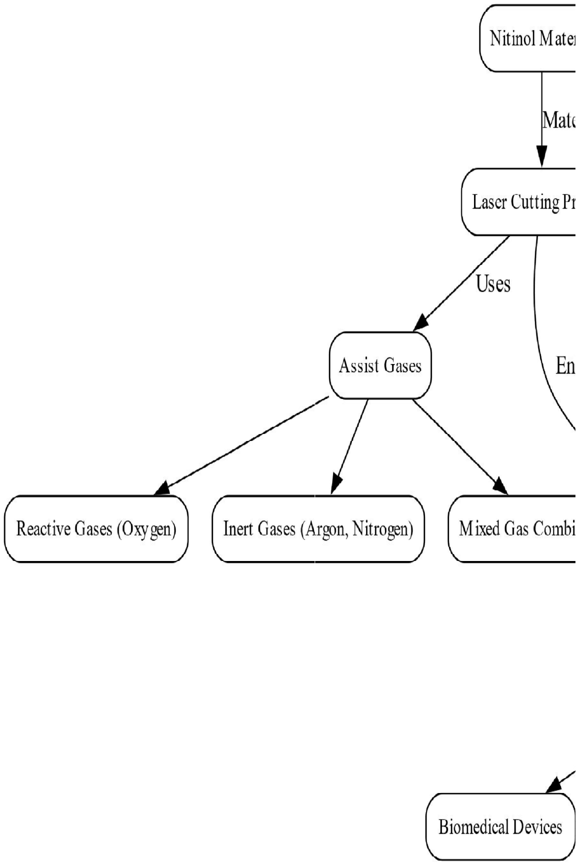

Figure 2. Process Flow of Nitinol Laser Cutting and Assist Gas

As illustrated, the laser cutting process benefits from the integration of optimized assist gas compositions, real-time process monitoring, and advanced material handling. The combination of reactive and inert gases provides a balance between cutting efficiency and surface quality. Further optimization strategies focus on reducing heat-affected zones, improving precision, and ensuring biocompatibility in critical applications such as medical implants and aerospace components.

The effectiveness and caliber of laser cutting in Nitinol are greatly influenced by the assist gas selection. Cutting speed, oxidation, surface polish, and overall thermal impacts are all influenced by various gases. The effect of frequently used assist gases on important cutting characteristics is summed up in the table below.

Table1- Effects of Assist Gases in Nitinol Laser Cutting:

Gas Type	Mechanism	Advantages	Disadvantages	Applications
Oxygen (O_2)	Reactive gas; undergoes exothermic reactions to enhance cutting speed	- Increased cutting speed due to additional heat generation - Lower laser power consumption	-Surface oxidation requires post-processing - Rougher surface finish - Wider heat-affected zone (HAZ)	High-speed cutting where post-processing is acceptable (e.g., industrial applications)
Argon (Ar)	Inert gas; prevents oxidation and	- Clean, high-quality cuts - Minimal HAZ	- Slower cutting speed - Higher operational	Medical device manufacturing (e.g.,

	provides a protective atmosphere	- Ensures biocompatibility	cost	stents, implants)
Nitrogen (N_2)	Semi-reactive; can form nitrides on the surface at high temperatures	- Good surface quality- Enhances corrosion resistance - Moderate cutting speed	- Nitridation may require additional processing - Higher energy consumption compared to oxygen	Applications requiring a balance between speed and quality (e.g., stents, aerospace components)
Argon-Oxygen Mixture	Synergistic effect; combines the benefits of both gases	- Balanced cutting speed and surface quality - Reduced post-processing requirements - Smaller HAZ	- Requires precise gas mixture control - Initial setup costs for gas mixing	Ideal for medical applications requiring high precision and moderate speed

It is clear from the table that reactive gases, such oxygen, speed up cutting through exothermic processes, but they can also cause more oxidation, necessitating post-processing. Slower cutting speeds are the price paid for inert gases like nitrogen and argon, which reduce oxidation and guarantee excellent surface quality. A balanced strategy that maximizes both speed and surface polish is provided by mixed gas compositions. In the medicinal, aeronautical, and industrial sectors, choosing the right gas composition based on particular application needs requires an understanding of these impacts.

IV. OPTIMIZATION STRATEGIES FOR ASSIST GAS APPLICATIONS

Optimizing assist gas applications in laser cutting is essential to balance efficiency, precision, and surface quality. Strategies include selecting appropriate gas compositions, optimizing flow rates, and synchronizing laser parameters to reduce defects like dross and heat-affected zones (HAZ). Combining reactive and inert gases has proven effective in achieving superior surface finishes while maintaining cutting speed. Advanced nozzle designs and gas flow delivery systems improve energy utilization and reduce oxidation. These optimizations are crucial for ensuring that Nitinol components retain their unique properties, such as superelasticity and biocompatibility, during high-precision laser cutting processes.

A. Reactive vs. Inert Gas Effects

Reactive and inert gases have distinct roles in laser cutting. Oxygen, a reactive gas, enhances cutting speeds by initiating exothermic reactions but may cause surface oxidation, requiring post-processing[3],[6],[7]. In contrast, inert gases like argon and nitrogen produce clean, oxidation-free cuts, maintaining surface smoothness and biocompatibility, though cutting speeds are slower[5],[6]. Mixed gas environments combine these effects, offering an optimal balance between speed and quality, particularly for intricate geometries[6],[7]. The choice of gas depends on the application's requirements, emphasizing precision for medical devices or speed for industrial components[2],[3],[6].Process Parameters and Gas Mixtures

Process parameters, including gas composition, flow rate, and laser energy, are critical to achieving optimal Nitinol laser cutting. Adjusting these parameters minimizes heat-affected zones and dross formation while improving edge quality. Oxygen-rich mixtures enhance cutting speeds, while argon or nitrogen reduces thermal damage and ensures surface integrity. Case studies highlight the benefits of specific argon-oxygen ratios in balancing cut precision and speed. Proper synchronization of gas mixtures with laser power and scanning speed can further optimize the process, ensuring repeatable and high-quality results in advanced Nitinol applications.

B. Real-Time Monitoring and Feedback Systems

Real-time monitoring systems significantly improve the precision and repeatability of Nitinol laser cutting by offering real-time control over thermal effects and gas flow dynamics[6],[7]. Thermographic imaging and optical sensors detect defects like oxidation, dross, and microstructural changes, allowing immediate adjustments during the process[2],[5],[6]. Feedback loops integrated into laser systems optimize cutting parameters, reducing waste and improving efficiency[3],[6]. These technologies enable high precision for intricate Nitinol applications, such as medical stents and aerospace actuators, ensuring superior surface quality and structural integrity[6],[7].

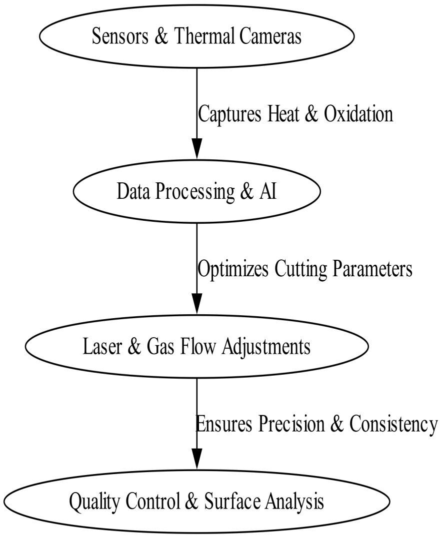

Figure 3- Real time monitoring and Feedback systems

As shown in the diagram, real-time monitoring plays a crucial role in adjusting laser parameters dynamically. Sensors capture thermal and structural data, which is processed using AI algorithms to detect irregularities such as oxidation, dross formation, and deviations in cut quality. Feedback loops then modify laser power, gas flow, and scanning speed in real time, enhancing precision, reducing material waste, and ensuring the consistency required for high-performance applications in biomedical, aerospace, and industrial sectors.

V. TRENDS, CHALLENGES, AND RESEARCH OPPORTUNITIES

The field of Nitinol laser cutting is rapidly advancing, driven by innovations in gas applications, laser technologies, and monitoring systems. However, challenges like optimizing mixed gas compositions, addressing HAZ, and minimizing environmental impacts remain significant. Research opportunities include developing machine learning algorithms for parameter optimization and studying the long-term effects of laser-processed Nitinol components. Addressing these gaps will enable the development of more efficient and sustainable cutting techniques, broadening the scope of Nitinol's application in critical industries like medicine and aerospace.

A. Emerging Trends in Nitinol Laser Cutting

Emerging trends include the integration of hybrid laser systems, combining femtosecond and nanosecond technologies, to improve precision and reduce thermal effects. The use of mixed gas environments tailored to specific applications is also gaining traction. Advanced monitoring systems employing AI and machine learning for process control are reshaping precision manufacturing. Furthermore, environmentally sustainable assist gases and energy-efficient delivery systems are becoming priorities, aligning with global efforts to reduce carbon footprints in manufacturing.

B. Challenges and Research Gaps

Despite advancements, challenges in Nitinol laser cutting include understanding the interplay of gas mixtures with cutting parameters and addressing surface oxidation caused by reactive gases[2],[6]. Research gaps persist in standardizing evaluation methods for cut quality and biocompatibility[5],[6]. Long-term effects of laser processing on Nitinol's mechanical and thermal properties remain understudied, limiting its application potential in critical fields[6],[7]. Addressing these gaps requires interdisciplinary research involving materials science, laser engineering, and biomedical expertise[3],[6],[7].

C. Future Research Directions

Future research should focus on integrating AI-driven models for optimizing laser parameters and gas compositions to improve efficiency and cut quality[6],[7]. Developing eco-friendly assist gases and enhancing real-time monitoring systems can address environmental and operational challenges[3],[6]. Additionally, investigating the long-term performance of laser-processed Nitinol in medical and aerospace applications will provide deeper insights into its reliability and durability, enabling broader adoption[5],[6],[7]. These efforts will drive innovations in Nitinol laser cutting and unlock its potential for advanced applications[2],[6].

VI. APPLICATIONS OF OPTIMIZED NITINOL LASER CUTTING

Optimized Nitinol laser cutting enables high-precision manufacturing across biomedical, aerospace, and emerging industries[3],[6],[7]. Enhanced surface quality, minimized thermal effects, and precise geometries make it ideal for producing intricate components. These applications benefit from advancements in assist gas optimization and laser technologies, ensuring superior functionality and durability[5],[6],[7].

A. Biomedical Applications

In the biomedical field, optimized laser cutting is essential for producing stents, catheters, and surgical tools with superior surface quality and biocompatibility[2],[5],[6]. Minimizing oxidation and thermal effects ensures that these devices maintain their structural and functional integrity during use[6],[7]. Precise laser cutting is critical for meeting stringent medical requirements for patient safety[3],[7].

B. Aerospace and Robotics

Nitinol's ability to withstand extreme conditions makes it ideal for aerospace actuators, morphing structures, and robotic components[6],[7]. Optimized laser cutting enables the precise fabrication of lightweight and durable parts, critical for performance in high-stress environments[3],[5],[6]. Advanced gas systems ensure excellent surface finishes, enhancing operational efficiency[2],[6].

C. Emerging Areas

Emerging applications of Nitinol laser cutting include flexible electronics, energy-efficient systems, and smart materials for IoT devices[6],[7]. Precision cutting ensures reliability and functionality in these advanced technologies. Furthermore, eco-friendly gas systems align with sustainable manufacturing trends, broadening the scope of Nitinol's applications in innovative fields[3],[5],[6].

VII. CONCLUSION

Advances in Nitinol laser cutting, particularly in assist gas optimization and monitoring technologies, have significantly improved processing precision and surface quality. These innovations have led to enhanced efficiency and better control over the laser-cutting process, ensuring that Nitinol components meet stringent industry requirements. Challenges like heat-affected zones (HAZ) and oxidation, which can impact material integrity and performance, are being actively addressed through the use of mixed gas applications and real-time control systems. These developments contribute to minimizing defects and improving the overall quality of laser-cut Nitinol components.Future research integrating AI-driven models and sustainable practices will unlock new opportunities for Nitinol in critical industries like medicine and aerospace. The application of artificial intelligence in laser cutting will enable real-time optimization of parameters, ensuring enhanced precision, reduced material wastage, and improved repeatability. Additionally, the adoption of eco-friendly manufacturing practices, such as the use of sustainable assist gases and energy-efficient laser systems, will contribute to reducing the environmental impact of laser processing.

By continuing to refine these advancements and addressing existing challenges, the potential of Nitinol laser cutting can be fully realized. As research progresses, new possibilities for high-precision manufacturing in medical implants, aerospace components, and other advanced engineering applications will emerge, further solidifying Nitinol's role as a key material in modern industry.

REFERENCES

[1] J. W. Mwangi, L. T. Nguyen, V. D. Bui, T. Berger, H. Zeidler, and A. Schubert, "Nitinol manufacturing and micromachining: A review of processes and their suitability in processing medical-grade nitinol," *J. Manuf. Process.*, vol. 38, pp. 355–369, 2019.

[2] C. R. Otto, A. Doroudi, M. Vaseghi, and K. Davami, "The effect of assist gas type on nitinol microsecond laser cut edges: a study on the use of oxygen, argon, nitrogen, helium, and compressed air," *Eng. Res. Express*, vol. 6, no. 4, p. 045583, 2024.

[3] Y. Zhang, C. Wang, W. Xu, X. Zhang, K. Ren, S. Wang, and Q. Hua, "Laser Cutting of Titanium Alloy Plates: A Review of Processing, Microstructure, and Mechanical Properties," *Metals*, vol. 14, no. 10, p. 1152, 2024.

[4] D. J. McGrath, M. Bruzzi, and P. E. McHugh, "Nitinol stent design–understanding axial buckling," *J. Mech. Behav. Biomed. Mater.*, vol. 40, pp. 252–263, 2014.

[5] J. Frenzel, A. Wieczorek, I. Opahle, B. Maaß, R. Drautz, and G. Eggeler, "On the effect of alloy composition on martensite start temperatures and latent heats in Ni–Ti-based shape memory alloys," *Acta Mater.*, vol. 90, pp. 213–231, 2015.

[6] J. C. Chekotu, R. Groarke, K. O'Toole, and D. Brabazon, "Advances in selective laser melting of nitinol shape memory alloy part production," *Materials*, vol. 12, no. 5, p. 809, 2019.

[7] B. Katona, E. Bognár, B. Berta, P. Nagy, and K. Hirschberg, "Chemical etching of nitinol stents," *Acta Bioeng. Biomech.*, vol. 15, no. 4, 2013.

[8] C. H. Fu, Y. B. Guo, and M. P. Sealy, "A predictive model and validation of laser cutting of nitinol with a novel moving volumetric pulsed heat flux," *J. Mater. Process. Technol.*, vol. 214, no. 12, pp. 2926–2934, 2014.

[9] H. Choi, M. Y. Na, I. Jun, H. Jeon, Y. C. Kim, J. W. Park, and H. J. Chang, "Repetitive nanosecond laser-induced oxidation and phase transformation in NiTi alloy," *Metals Mater. Int.*, vol. 30, no. 5, pp. 1200–1208, 2024.

[10] S. Shabalovskaya, J. Anderegg, and J. Van Humbeeck, "Critical overview of Nitinol surfaces and their modifications for medical applications," *Acta Biomater.*, vol. 4, no. 3, pp. 447–467, 2008.

[11] G. B. Kauffman and I. Mayo, "The story of nitinol: the serendipitous discovery of the memory metal and its applications," *Chem. Educ.*, vol. 2, no. 2, pp. 1–21, 1997.

[12] J. Mohd Jani, M. Leary, A. Subic, and M. A. Gibson, "A review of shape memory alloy research, applications and opportunities," *Mater. Des.*, vol. 56, pp. 1078–113, 2014.

[13] D. Kapoor, "Nitinol for medical applications: a brief introduction to the properties and processing of nickel titanium shape memory alloys and their use in stents," *Johnson Matthey Technol. Rev.*, vol. 61, no. 1, pp. 66–76, 2017.

[14] J. Ryhänen, *Biocompatibility Evaluation of Nickel-Titanium Shape Memory Metal Alloy*, Oulun yliopisto, 1999. DOI: 10.1007/BF03037208.

[15] C. DellaCorte, "NiTi Alloys for Structural and Tribological Applications: The Other Side of Superelastics," presented at *International Conference on Shape Memory and Superelastic Technologies (SMST)*, May 2016.

[16] J. W. Mwangi, H. Zeidler, R. Kühn, and A. Schubert, "Suitability assessment of micro-EDM in machining Nitinol for medical applications," in *Euspen's 16th Int. Conf. & Exhib.*, pp. 189–190, 2016.