Major Project Report

on

Case Study of shape memory alloy in biomedical application

Submitted in the Partial Fulfilment of the Requirements for the Award of the Degree of

Bachelor of Technology

in

Mechatronics and Automation Engineering

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INDIAN INSTITUTE OF INFORMATION TECHNOLOGY BHAGALPUR
(An Institute of National Importance under Act of Parliament)

DECLARATION

We hereby declare that the work reported in this thesis on the topic "**Case study of shape memory alloy in biomedical application**" is original and has been carried out by us independently in the **Department of Mechatronics and Automation Engineering, IIIT Bhagalpur** under the supervision of **Dr. Tameshwer Nath,** Assistant Professor, Department of Mechatronics and Automation Engineering, IIIT Bhagalpur. We also declare that this work has not been the basis for the award of any other Degree, Diploma, or similar title of any university or institution.

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CERTIFICATE

This is to certify that the thesis entitled "**Case study of shape memory alloy in biomedical application**" is carried out by **Saket Kumar (Roll No: 2001099) and Nishi Singh (Roll No: 2001076),** undergraduate student of IIIT Bhagalpur, under my supervision and guidance. This thesis has been submitted in partial fulfilment for the award of degree of **Bachelor of Technology** in **Mechatronics and Automation Engineering** at **Indian Institute of Information Technology, Bhagalpur**.

No part of this thesis has been submitted for the award of any previous degree to the best of my knowledge.

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ABSTRACT

Shape Memory Alloys (SMAs) are super cool materials that can change their shape when heated or stressed and then go back to their original shape when cooled down. They're like magic metals that can remember their old forms! These SMAs are getting a lot of attention in medical engineering because they have special abilities that make them perfect for all sorts of medical devices.

Think about how a spring can stretch and then bounce back. SMAs can do something similar, but they can also change their shape completely and then change back again without losing their strength. This makes them great for things like stents (which hold open blocked blood vessels), braces (which help straighten teeth), surgical tools, and even implants that can slowly break down safely inside the body.

They're also being used in devices for the nervous system, like sensors that can detect and respond to changes in the body. Plus, they're being tested for use in artificial limbs, where their strength and flexibility could make a huge difference.

But using SMAs in medical tools isn't always easy. Sometimes they can be tricky to control, and there's still a lot of research needed to make sure they work perfectly every time. However, scientists and engineers are working hard on new improvements, and these SMA materials are getting more popular in medical devices every day.

In the future, we might see even more exciting uses for SMAs in medicine. Imagine tiny drug delivery systems that can release medicine exactly where it's needed or dental tools that can reshape themselves to fit each patient perfectly. The possibilities are endless, and SMAs are definitely playing a big role in shaping the future of medical engineering.

This paper talks about how SMAs are used in medical devices like stents, braces, surgical tools, drug delivery systems, dental tools, implants that break down in the body, devices for the nervous system, and artificial limbs. It explains the basic ideas behind SMAs, how well they work with the body, their strength and flexibility, and the problems of using them in medical tools. The paper also talks about new improvements, what’s becoming popular, and the future of using SMAs in medical engineering.

Chapter 1: Introduction

1.1. Overview

SMAs are special types of metals that can remember their original shape even after being bent, stretched, or deformed. This ability is due to a reversible change in their internal structure when they experience certain conditions like changes in temperature or applied stress.

The most common type of SMA is made from a combination of nickel and titanium, often called Nitinol. Other types of SMAs can be made using copper or other metals. These alloys have excellent mechanical properties, meaning they are strong, flexible, and can withstand repeated use without breaking.

The unique atomic arrangement within SMAs allows them to shift and rearrange their structure during phase transitions (changes in temperature or stress). This rearrangement enables them to return to their original shape when the conditions causing the deformation are removed.

Because of their ability to recover their shape and withstand stress, SMAs are used in various fields. In medicine, they are used in stents (to keep blood vessels open), orthodontic wires (to straighten teeth), and surgical instruments (to manipulate tissues). They are also used in aerospace engineering for components that need to withstand extreme conditions and in robotics for components that need to be flexible and responsive.

Engineers are exploring ways to further enhance SMAs' capabilities, such as creating materials that can repair themselves when damaged or change shape in response to specific stimuli. This ongoing research and development continue to expand the potential applications of SMAs in different industries.

1.2. Fundamentals of Shape memory alloys

The most used SMA is Nickel-Titanium (NiTi), also known as Nitinol, which exhibits exceptional properties such as shape memory effect, super elasticity, biocompatibility, and corrosion resistance. These properties make NiTi highly suitable for various biomedical applications.

Nitinol's shape memory effect refers to its ability to return to its original shape after deformation when exposed to the appropriate stimulus. Super elasticity describes Nitinol's ability to undergo large deformations and still return to its original shape. These characteristics have led to the use of NiTi in various fields, including medicine, aerospace, robotics, and more. In the biomedical field, Nitinol is commonly used in applications such as stents, guidewires, orthodontic braces, and surgical instruments due to its biocompatibility and unique mechanical properties.

1.2.1. Shape Memory Effect

The shape memory effect in Shape Memory Alloys (SMAs) refers to the material's ability to recover its original shape after deformation when subjected to a specific stimulus, typically a change in temperature [1]. When an SMA is in its austenite phase, it can be deformed into a different shape. Upon cooling below a critical temperature, known as the martensitic transformation temperature, the material transforms into a martensite phase and retains the deformed shape. Subsequent heating above the transformation temperature causes the material to revert to its original shape, exhibiting the shape memory effect.

This unique behaviour is a result of a reversible solid-state phase transformation between the austenite and martensite phases of the SMA. When the SMA is deformed in its high-temperature austenite phase and cooled to activate the martensitic phase, the material retains the deformed shape due to the reorientation of the martensite variants [2]. Heating the material above the transformation temperature causes the martensite phase to revert back to the austenite phase, resulting in the recovery of the original shape, thus showcasing the shape memory effect of SMAs.

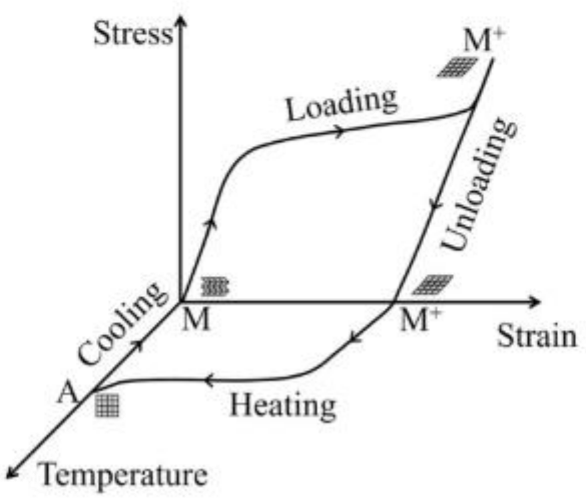


Fig. 1.1 Shape memory effect

1.2.2. Super elasticity

Super elasticity, also known as pseudo elasticity, is another unique property of Shape Memory Alloys (SMAs), particularly NiTi alloys. Unlike traditional elastic materials, SMAs can undergo large reversible deformations without undergoing permanent plastic deformation [3-4]. This property is especially advantageous in biomedical applications where devices need to withstand significant stress and strain, such as in stents or orthodontic wires.

The super elasticity of SMAs like NiTi arises from a reversible phase transformation between austenite and martensite phases. When the material is deformed, instead of permanently altering its structure like traditional materials, the SMA's martensitic phase allows it to undergo substantial deformations. Upon removal of the applied stress, the material returns to its original shape as it transitions back to the austenitic phase [5-6]. This unique behaviour enables SMAs to absorb and recover from large deformations, making them ideal for applications requiring flexibility, durability, and resilience to mechanical forces. In the field of medicine, super elastic Niti alloys are commonly utilized in devices such as stents and orthodontic wires where the ability to undergo significant deformation without permanent damage is crucial for long-term performance and biocompatibility.

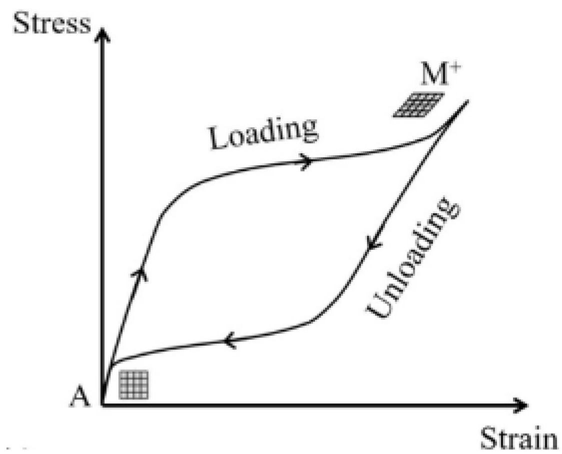


Fig. 1.2 Super elasticity

1.2.3. Biocompatibility and Corrosion Resistance

Shape Memory Alloys (SMAs), particularly NiTi alloys, are known for their excellent biocompatibility, making them suitable for implantable medical devices and applications within the human body [1,7]. Additionally, these alloys exhibit high corrosion resistance, ensuring long-term stability and performance in physiological environments.

The biocompatibility of NiTi alloys refers to their ability to coexist with living tissues, cells, and bodily fluids without causing adverse reactions or harm. This property is crucial for implantable medical devices like stents, orthodontic wires, bone plates, and surgical instruments that come into direct contact with the human body. The high corrosion resistance of NiTi alloys further reinforces their suitability for such applications, as it protects the material from degradation when exposed to bodily fluids and environments.

The combination of excellent biocompatibility and corrosion resistance in NiTi alloys enhances the overall safety, reliability, and longevity of medical devices used in various procedures, contributing to successful outcomes and patient well-being. These properties make NiTi alloys a preferred choice for a wide range of biomedical applications, where performance, durability, and compatibility with the human body are essential factors to consider.

1.3. Importance in biomedical application

Shape Memory Alloys (SMAs) are becoming more popular in medical engineering because they have some fantastic qualities. One of the best things about them is that they're gentle on the body [10]. This means they don't cause any harm or irritation when they're used in medical devices or implants. Another great feature of SMAs is their ability to resist rust well. This is important because they can be used inside the body for a long time without getting damaged.

But the most exciting thing about SMAs is that they can bend a lot without losing their original shape. This is super helpful in medicine because it means they can be used in devices that need to move precisely and stay in the right form.

We can only imagine SMAs being used in all kinds of new medical tools and devices. They could help doctors do better diagnoses and treatments, making healthcare even more effective. The future looks really promising for SMAs in healthcare technology, with lots of opportunities to improve [11].

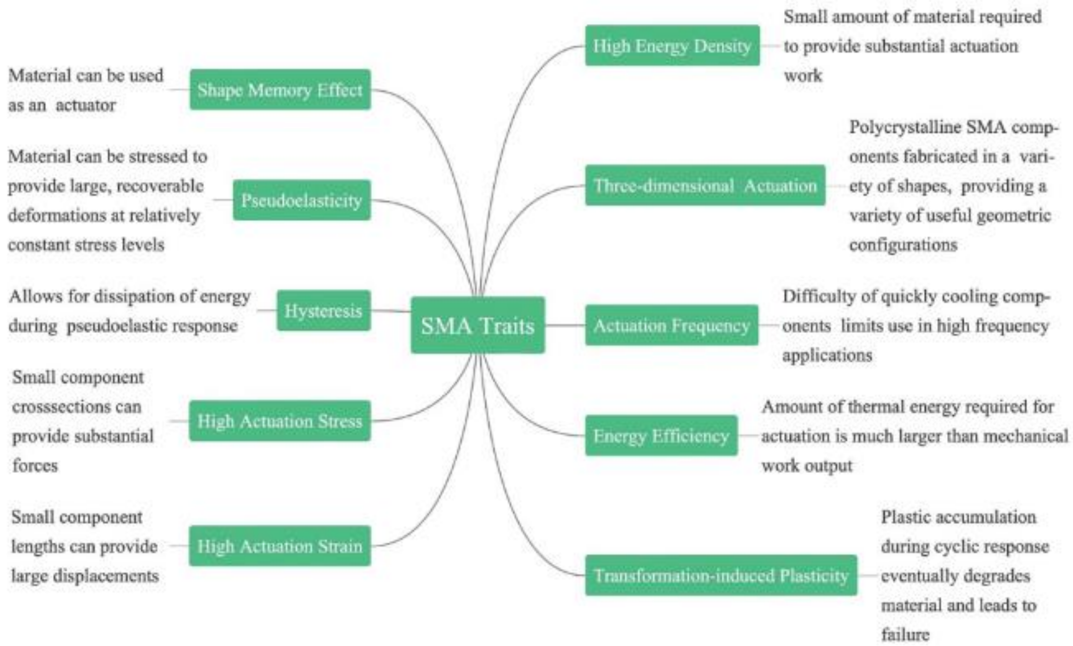


Fig. 1.3 The trait of SMAs

1.4. Objectives

- Provide a comprehensive overview of SMAs in biomedical applications.
- Explore fundamental principles and mechanical properties of SMAs.
- Discuss challenges related to integrating SMAs into biomedical devices.
- Examine specific biomedical applications, recent advancements, and emerging trends in the field.
- Synthesize existing literature and key findings to contribute to a deeper understanding of SMAs' potential in healthcare.
- Aim to revolutionize healthcare delivery, improve patient outcomes, and stimulate further research and innovation in biomedical engineering.

Chapter 2: Application of SMAs in biomedical

2.1. Introduction:

While there are some options of SMAs to choose from like Nitinol, Cu-Al-Ni, Cu-Zn-Al but we choose to go ahead with NiTi alloy usually because they are known for their excellent biocompatibility, making them suitable for implantable medical devices and applications within the human body. Additionally, these alloys exhibit high corrosion resistance, ensuring long-term stability and performance in physiological environments.

The biocompatibility of NiTi alloys refers to their ability to coexist with living tissues, cells, and bodily fluids without causing adverse reactions or harm. This property is crucial for implantable medical devices like stents, orthodontic wires, bone plates, and surgical instruments that come into direct contact with the human body [12]. The high corrosion resistance of NiTi alloys further reinforces their suitability for such applications, as it protects the material from degradation when exposed to bodily fluids and environments.

The combination of excellent biocompatibility and corrosion resistance in NiTi alloys enhances the overall safety, reliability, and longevity of medical devices used in various procedures, contributing to successful outcomes and patient well-being.

Biomedical Applications of Shape Memory Alloys are:

2.2. Stents:

Stents are widely used in the treatment of coronary artery disease to restore blood flow in narrowed or blocked arteries. Shape Memory Alloys (SMAs), particularly Nickel-Titanium (NiTi) alloys, are commonly employed in the fabrication of stents due to their super elasticity and biocompatibility [9]. These properties allow the stent to be compressed to a smaller diameter for insertion into the artery and then expanded to its original shape upon deployment. SMAs ensure adequate radial force to keep the artery open while minimizing the risk of vessel injury or restenosis.

2.2.1. Design Considerations:

- Optimization of stent design to achieve proper radial strength, flexibility, and conformability to the vessel wall.

- Selection of SMA composition and processing techniques to ensure optimal mechanical properties and biocompatibility.
- Incorporation of drug-eluting coatings to prevent restenosis and promote healing.

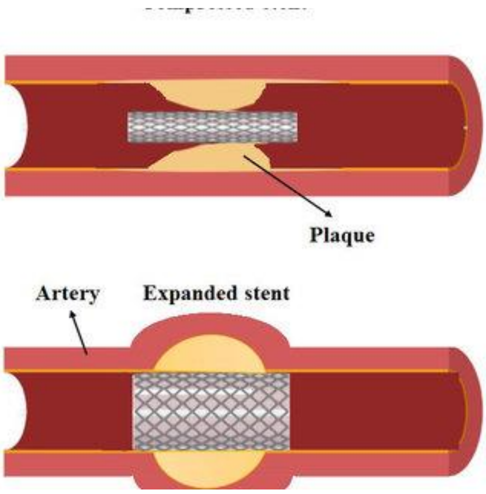


Fig. 2.1 SMA Stent

2.2.2. Performance and Clinical Outcomes:

- Studies have shown favourable clinical outcomes with SMA-based stents, including reduced rates of restenosis and improved long-term patency [13].
- Advancements in stent technology continue to improve device deliverability, flexibility, and customization to patient anatomy.

2.2.3. Current Challenges and Future Directions:

- Addressing issues such as stent thrombosis, late stent malposition, and endothelialisation to further enhance the safety and efficacy of SMA-based stents.
- Integration of bioresorbable materials and advanced surface modifications to promote vascular healing and minimize long-term complications.

2.3. Surgical Instruments:

Shape Memory Alloys (SMAs) are increasingly used in the manufacturing of surgical instruments for minimally invasive procedures. These instruments can be designed to change shape in response to temperature changes, allowing for precise control and manipulation within the surgical site [14]. Additionally, SMAs offer advantages such as biocompatibility, corrosion resistance, and high mechanical strength, making them suitable for various surgical applications.

The unique properties of SMAs, including their shape memory effect and super elasticity, enable the development of surgical instruments that can adapt to the specific needs of minimally invasive surgeries. By utilizing SMA technology, these instruments can be designed to navigate complex anatomical structures with enhanced precision and flexibility, ultimately improving surgical outcomes and patient recovery.

In addition to their shape-shifting capabilities, SMAs provide inherent benefits like biocompatibility, ensuring compatibility with biological tissues and reducing the risk of adverse reactions. Their corrosion resistance and high mechanical strength further enhance the durability and longevity of surgical instruments, making them well-suited for use in a wide range of su3gical procedures where precision, reliability, and patient safety are paramount [15].

2.3.1. Types of Instruments:

- SMA-based instruments include graspers, forceps, retractors, and catheters used in laparoscopic, endoscopic, and robotic-assisted surgeries.
- Smart instruments with integrated sensors and actuators enable real-time feedback and enhanced dexterity for surgeons.

2.3.2. Minimally Invasive Surgery:

- SMAs enable the development of smaller, more flexible surgical instruments, reducing tissue trauma, postoperative pain, and recovery time for patients.
- Precise control and manipulation afforded by SMA-based instruments improve surgical outcomes and minimize the risk of complications.

2.3.3. Temperature-responsive Instruments:

- Thermally activated SMAs allow instruments to change shape in response to body temperature or external heating sources, enhancing manoeuvrability and functionality.
- Shape memory effect enables instruments to return to their original shape after deformation, ensuring consistent performance throughout the surgical procedure.

These applications highlight the versatility and potential of Shape Memory Alloys (SMAs) in biomedical engineering, offering innovative solutions to address clinical needs and improve patient outcomes in diverse medical specialties. Ongoing research and development efforts aim to further enhance the performance, functionality, and integration of SMAs in biomedical devices and systems.

2.4. Drug Delivery Systems:

Shape Memory Alloys (SMAs) have shown significant potential in the development of innovative drug delivery systems capable of targeted and controlled release of therapeutic agents [1,16]. These systems leverage the unique properties of SMAs, including shape memory effect and biocompatibility, to precisely deliver drugs to specific anatomical sites within the body, thereby improving therapeutic efficacy and reducing side effects.

2.4.1. Controlled Release Mechanisms:

Temperature-Responsive Systems: SMAs can be integrated into drug delivery systems as temperature-responsive components, allowing for controlled release of drugs in response to changes in local temperature within the body. Upon reaching the target site, the SMA undergoes a reversible phase transformation, triggering the release of encapsulated drugs.

2.4.2. Shape Memory Polymers:

SMA-based shape memory polymers (SMPs) are being investigated for their potential in controlled drug release applications [17]. These SMPs can be programmed to undergo reversible shape changes in response to external stimuli, such as temperature or pH, enabling on-demand release of drugs at predetermined intervals.

2.4.3 Stimulus-Responsive Delivery:

pH-Sensitive Systems: SMA-based drug delivery systems can be designed to respond to changes in pH levels within the body, such as those associated with tumour microenvironments or gastrointestinal tract. pH sensitive SMAs undergo conformational changes in response to acidic or alkaline conditions, leading to controlled release of drugs at the desired location.

2.4.4. External Stimuli:

SMAs can also be activated by external stimuli, such as magnetic fields or ultrasound waves, to trigger drug release from implanted or injectable devices. This approach offers precise control over drug delivery kinetics and spatial distribution, minimizing systemic exposure and off-target effects.

2.4.5. Applications in Targeted Therapy:

Cancer Therapy: SMA-based drug delivery systems hold promise for targeted cancer therapy, allowing for localized delivery of chemotherapeutic agents to tumour tissues while minimizing damage to healthy cells. By enhancing drug accumulation at the tumour site, these systems improve therapeutic efficacy and reduce systemic toxicity.

2.4.6. Neurological Disorders:

SMA-based drug delivery systems are being explored for the treatment of neurological disorders, such as epilepsy and Parkinson's disease. By delivering neuroactive drugs directly to affected brain regions, these systems offer the potential to improve symptom management and disease progression.

2.4.7. Future Directions:

Multifunctional Platforms: Future research aims to develop multifunctional SMA-based drug delivery platforms capable of integrating diagnostics, imaging, and therapeutic functionalities into a single device. These platforms offer personalized treatment options and real-time monitoring of drug responses, enhancing patient care and clinical outcomes.

2.4.8. Biomimetic Designs:

Biomimetic approaches, inspired by nature, are being pursued to develop SMA-based drug delivery systems that mimic biological processes and responses. By harnessing the principles of biomimicry, researchers aim to design highly efficient and biocompatible drug delivery platforms with improved targeting and tissue penetration capabilities.

2.4.9. Clinical Translation:

The translation of SMA-based drug delivery systems from bench to bedside remains a key challenge. Future efforts will focus on preclinical studies, regulatory approval processes, and clinical trials to validate the safety, efficacy, and scalability of these innovative drug delivery technologies for widespread clinical use [19].

In conclusion, Shape Memory Alloys (SMAs) offer exciting opportunities for the development of advanced drug delivery systems with precise control over drug release kinetics and spatial distribution. Continued research and development in this field hold promise for transforming the landscape of targeted therapy and personalized medicine, ultimately improving patient outcomes and quality of life.

2.5. Dental Applications:

Shape Memory Alloys (SMAs), particularly Nickel-Titanium (NiTi) alloys, have found numerous applications in dentistry, ranging from orthodontic treatment to endodontic procedures and dental implants. The unique mechanical properties and biocompatibility of

SMAs make them well-suited for various dental applications, offering benefits such as improved treatment outcomes, patient comfort, and durability.

2.5.1. Orthodontics:

Orthodontic Wires: NiTi wires are widely used in orthodontic treatment to apply continuous and gentle forces to teeth, promoting tooth movement and alignment. The super elasticity of NiTi wires allows for controlled tooth movement while minimizing discomfort for the patient [20]. Additionally, NiTi wires exhibit shape memory effect, enabling them to return to their original shape after deformation, ensuring consistent force delivery throughout treatment.

Arch wires and Brackets:

SMA-based arch wires and brackets are designed to provide optimal tooth alignment and stability during orthodontic treatment. These components are available in various shapes, sizes, and configurations to accommodate different treatment needs and preferences. SMA-based arch wires and brackets offer advantages such as reduced treatment time, fewer adjustments, and improved patient comfort compared to traditional orthodontic materials.

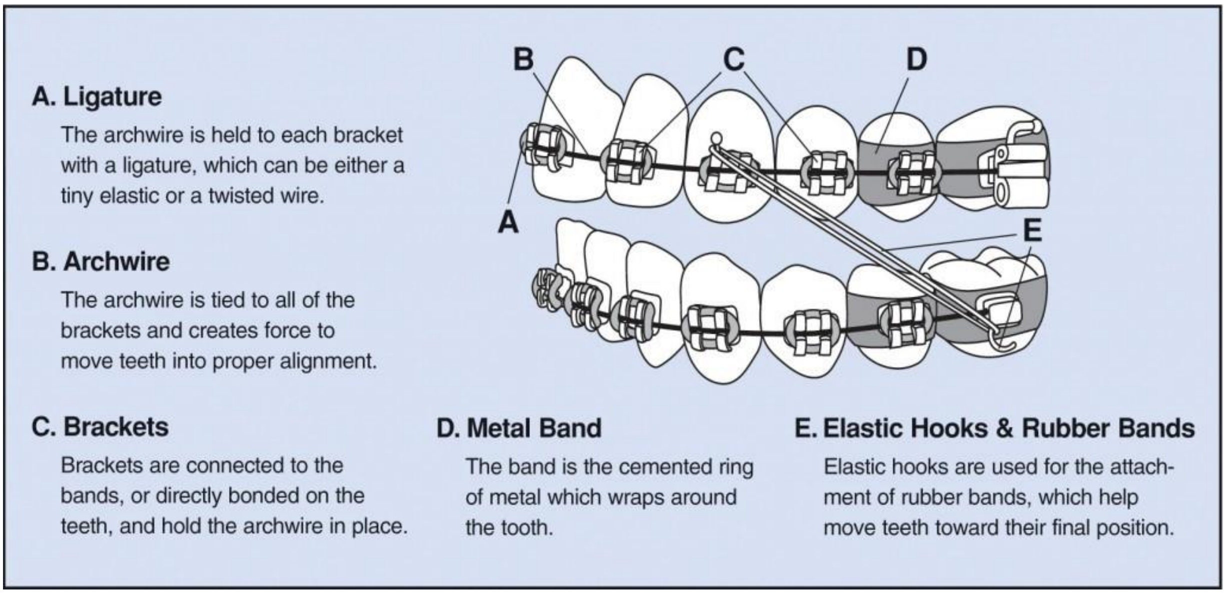


Fig. 2.2 Orthodontic Wire

2.5.2. Endodontics:

Endodontic Files: SMA-based endodontic files are used in root canal therapy to remove infected or damaged tissue from the root canal system. NiTi files offer superior flexibility, durability, and resistance to cyclic fatigue compared to stainless steel files, allowing for more efficient and predictable root canal preparation [21]. The flexibility of NiTi files enables them to navigate curved and calcified root canals with greater ease, reducing the risk of procedural errors and improving treatment outcomes.

Fig. 2.3 Endodontic Files

Obturation Techniques:

SMA-based obturation techniques, such as thermoplastic zed gutta-percha, are utilized to fill and seal the root canal system following cleaning and shaping procedures. NiTi-based obturation techniques offer improved adaptation to the root canal walls, enhanced sealing properties, and reduced risk of voids or gaps compared to conventional methods [4,22]. These techniques help prevent reinfection and promote healing of periapical tissues, ensuring long-term success of root canal therapy.

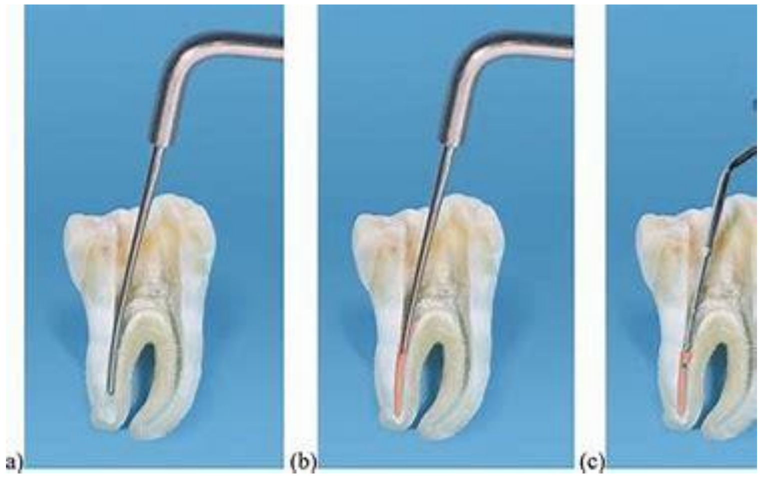


Fig. 2.4 SMAs obturation tool

2.5.3. Dental Implants:

Implant Materials: SMA-based dental implants are gaining popularity due to their biocompatibility, corrosion resistance, and mechanical properties similar to natural bone. NiTi implants offer advantages such as osseointegration, enhanced stability, and reduced risk of peri-implant complications compared to traditional implant materials. SMA-based implants can be customized in terms of size, shape, and surface characteristics to meet the specific needs of individual patients and clinical scenarios.

Fig. 2.5 Dental Implants

Guided Bone Regeneration:
SMA-based membranes and scaffolds are utilized in guided bone regeneration procedures to promote the growth of new bone tissue and enhance the stability of dental implants. These biocompatible materials provide a barrier to prevent soft tissue ingrowth into the defect site while allowing for the infiltration of osteogenic cells and vascularization. SMA-based membranes and scaffolds facilitate optimal bone regeneration and integration of dental implants, leading to improved implant success rates and long-term clinical outcomes.

In summary, Shape Memory Alloys (SMAs) have revolutionized various aspects of dentistry, including orthodontics, endodontics, and dental implantology. The unique mechanical properties and biocompatibility of SMAs offer numerous advantages for dental applications, contributing to improved treatment outcomes, patient satisfaction, and long-term oral health. Continued research and innovation in this field will further expand the capabilities and applications of SMA-based dental materials and technologies, benefiting both patients and dental practitioners.

2.6. Biodegradable Implants:

Shape Memory Alloys (SMAs) have gained attention in the field of biomedical engineering for the development of biodegradable implants with tailored mechanical properties and controlled degradation profiles. Biodegradable implants based on SMAs offer several advantages, including reduced risk of implant-related complications, elimination of the need for implant removal surgeries, and potential for tissue regeneration and remodelling [23]. These implants hold promise for various medical applications, ranging from orthopaedics to cardiovascular interventions.

2.6.1. Degradation Mechanisms:

Corrosion Degradation:

Biodegradable SMAs degrade primarily through corrosion in physiological environments. The gradual dissolution of the alloy releases metal ions into the surrounding tissue, which are metabolized or excreted by the body. The degradation rate can be tailored by adjusting the composition and processing parameters of the SMA, allowing for precise control over the implant's degradation kinetics and mechanical integrity.

Surface Modification:

Surface modifications, such as coatings or biocompatible layers, can be applied to biodegradable SMA implants to modulate their degradation behaviour and biocompatibility. These surface treatments can enhance tissue integration, minimize inflammatory responses, and promote favourable host responses to the degrading implant.

2.6.2. Applications and Benefits:

Orthopaedic Implants:

Biodegradable SMA implants show promise for orthopaedic applications, such as fracture fixation devices, bone screws, and scaffolds for bone regeneration. These implants provide temporary mechanical support and promote bone healing while gradually degrading and being replaced by newly formed bone tissue. Biodegradable SMAs offer advantages such as reduced stress shielding, improved bone remodelling, and avoidance of long-term implant-related complications.

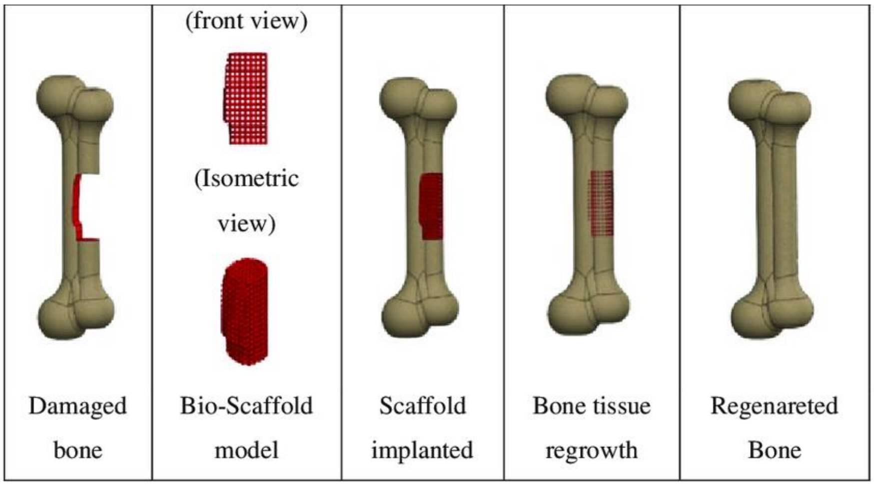


Fig. 2.6 Orthopaedic Implants

Cardiovascular Stents:

Biodegradable SMA stents are being investigated as alternatives to permanent metal stents for the treatment of coronary artery disease. These stents provide temporary vessel support and drug delivery capabilities while promoting endothelialisation and preventing restenosis. Biodegradable SMA stents offer the potential to restore vessel function and then degrade, eliminating the risk of late stent thrombosis and allowing for natural vessel remodelling over time.

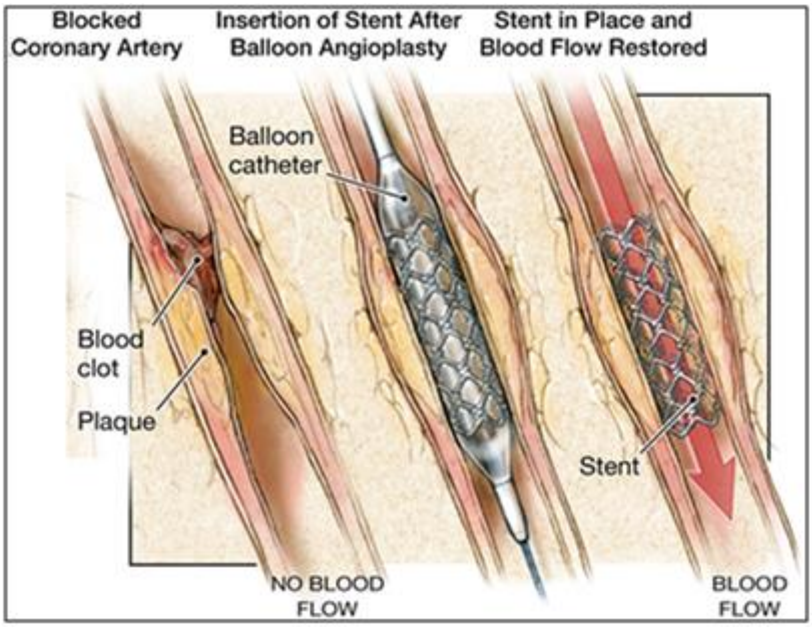


Fig. 2.7 Cardiovascular stent

2.6.3. Biocompatibility Considerations:

Host Response:

Biodegradable SMA implants elicit controlled inflammatory responses and tissue remodelling processes as they degrade, ultimately leading to integration with surrounding tissues and restoration of normal physiological function. The biocompatibility of these implants depends on factors such as degradation products, surface characteristics, and host immune responses.

In Vivo Evaluation:

Preclinical studies and animal models are utilized to evaluate the biocompatibility, degradation kinetics, and tissue responses of biodegradable SMA implants in vivo. These studies provide valuable insights into the safety, efficacy, and long-term performance of the implants before clinical translation.

Chapter 3: Experimentation

3.1. Introduction:

There have been several discussions over the past few decades as to whether SMAs can respond rapidly. As discussed in the literature review from previous chapter, researchers have chosen Ni-Ti in various forms due to its unique properties such as shape memory effect, super-elasticity, high damping capacity, high kinetic output, noise-less operation largest actuation force among actuators [25]. In this chapter, a novel experimental set up has been fabricated for life cycle estimation of SMA through electrical actuation.

The hysteresis response of Ni-Ti is highly dependent on the applied load and temperature. Life cycle estimation of SMA can be done by using heating and cooling, in which Joule heating plays an important role to actuate SMA, for cooling natural convection and radiation is the best option. SMA material is actuated via Joule heating and proposed for a different application which is discussed below. Parameters which have varied during experimentation are voltage, load, and displacement. For its development, it was required to know the stiffness of NiTi SMA. Therefore, the stiffness of NiTi spring is measured initially.

Fig. 3.1 SMA Spring with load

Parameters	Value
Coil Diameter (D)	3.5 mm
Wire diameter (d)	1.5 mm
Number of Turns (n)	20
Length of spring (l)	n*d = 30 mm (compressed)

Table 3.1 SMA Spring specification

3.2. Procedure to measure Stiffness:

Displacement of the spring was measured using digital venire caliper by varying the load applied in the steps of 0.5N each starting from 1.0 N to 3.5 N which was limited by the capacity of the spring.

It was observed that the plot between force vs. extension was not linear for the entire range of forces utilized. Since the properties of SMA vary in high degrees as compared to any steel alloy, this non-linearity was highly expected, Further, when the curve was broken into linear segments, equation for the each of them found to have some constant term as shown in Fig 3.2, which is the unique property of all tension springs known as "prestressing".

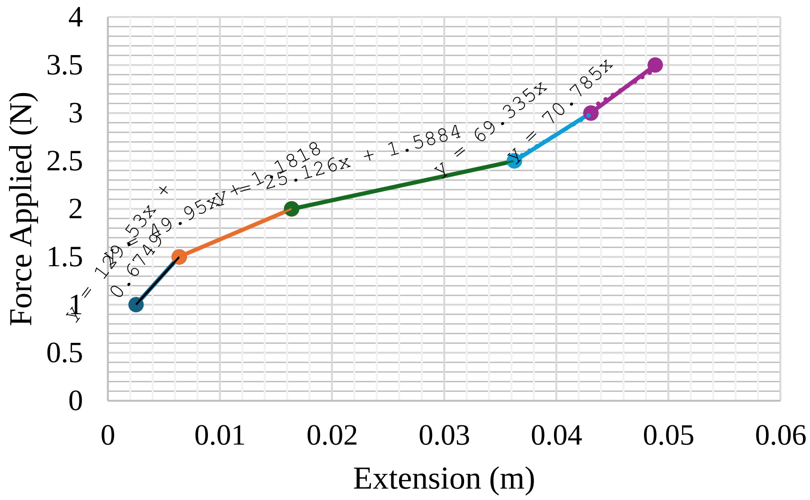


Fig. 3.2 Force applied vs extension of the SMA tension spring

Therefore, from these results, the spring constant (spring stiffness) values for different loads were obtained along with the pre-stress values which are mentioned in Table 3.2.

Force Range (N)	Spring stiffness (N/m)	Pre-stress value (N)
1.0-1.5	129.53	0.6749
1.5-2.0	49.95	1.1818
2.0-2.5	25.13	1.5884
2.5-3.0	69.34	0
3.0-3.5	70.79	0

Table 3.2 Results from the testing of the SMA tension spring

3.3. Experimentation of SMA spring in hot water:

Using a nitinol wire in a hot water bath process is a way to take advantage of its unique properties. First, we start by choosing a nitinol wire that can change its shape when heated. Then, we prepare a container of hot water, making sure the temperature is higher than the nitinol wire's transformation temperature, which is usually between 70°C to 100°C (158°F to 212°F). Next, we deform the nitinol wire into the shape we want, like bending or twisting it. After that, we immerse the deformed wire into the hot water bath, ensuring it's fully submerged and the water temperature stays constant. As the wire heats up in the water, it starts to revert back to its original shape due to the shape memory effect of nitinol. Once it has fully transformed back to its original shape, we take it out of the water and let it cool down to room temperature. Finally, we test the wire to see if it works as intended in its restored shape. This process is commonly used in various applications such as actuators, biomedical devices, and robotics where precise shape changes based on temperature are needed.

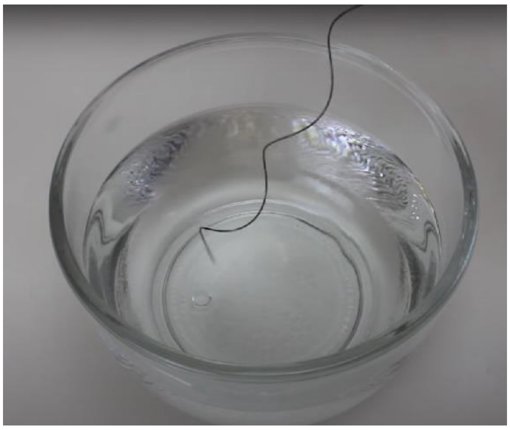


Fig. 3.3 Elongated spring

Fig. 3.4 Heat treated spring

Chapter 4: Morphological Analysis

FESEM, or Field Emission Scanning Electron Microscopy, is a powerful tool used to examine materials at a very detailed level. When studying a Shape Memory Alloy (SMA) wire, which is known for its ability to return to a predetermined shape after deformation, before and after exposing it to a hot water bath, several changes were observed[23-24].

Before the load treatment, the SMA wire's microstructure appeared uniform and intact under FESEM. However, after exposure to the additional load, noticeable changes occurred. The grain size of the material increase, indicating potential recrystallization or grain growth phenomena due to the electric treatment. Surface morphology also changed, with possible variations in roughness or the presence of new surface features like cracks or pits.

Understanding these microstructural changes is vital for optimizing the performance of SMA wires in various applications. For example, in biomedical devices like stents or actuators in robotics, where SMA wires are commonly used due to their ability to respond to temperature changes, knowing how they behave under specific thermal conditions helps in designing more reliable and efficient devices.

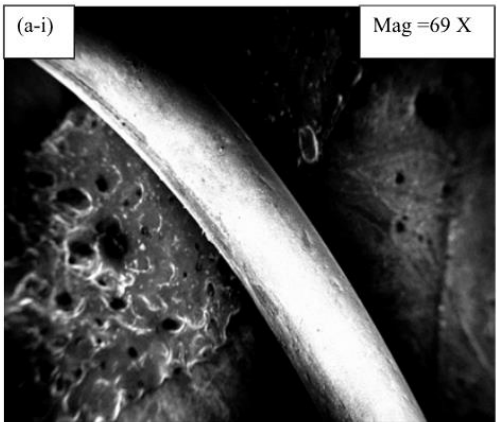


Fig.4.1 Fresh Spring

Fig. 4.2 Heat treated spring

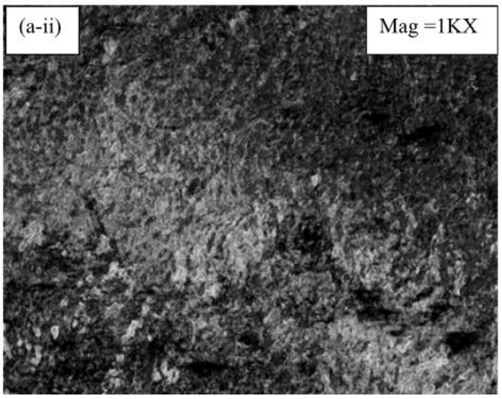


Fig.4.3 Fresh Spring

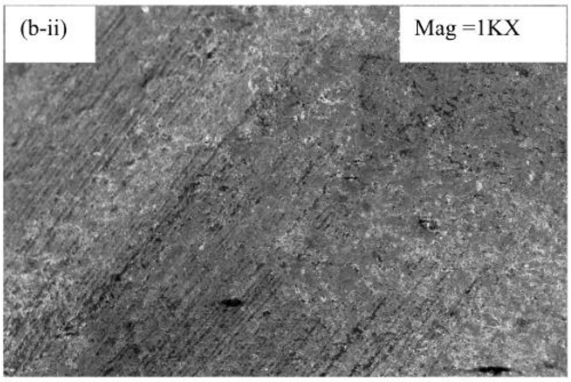
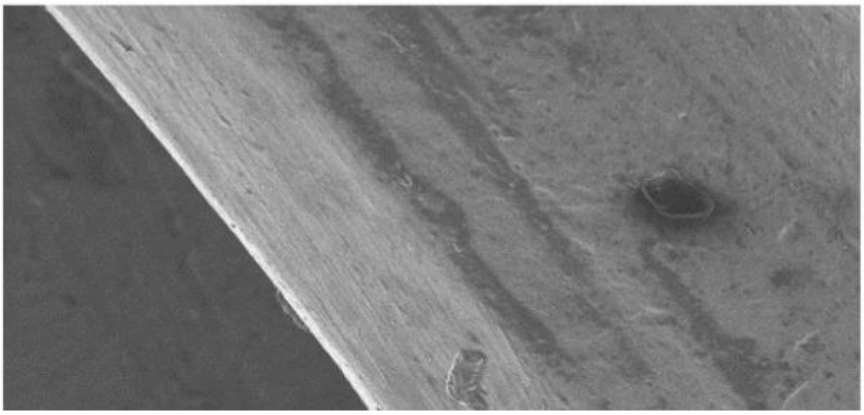


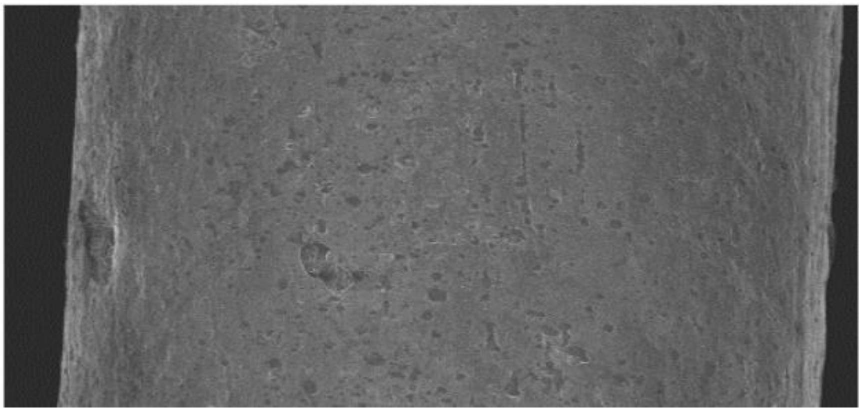
Fig. 4.4 Heat treated spring



20 μm EHT = 5.00 KV Signal A = InLens

WD = 5.8 mm Mag = 1.06 K X

Fig. 4.5 Fresh Spring



1 μm EHT = 5.00 kV Signal A = InLens

WD- 3.6 mm Mag = 40.00 K X

Fig. 4.6 Spring after failure

As the Shape Memory Alloy (SMA) wire underwent multiple cycles of load addition, its properties progressively declined, a trend vividly illustrated in the Thermogravimetric Analysis (TGA) graph [5]. This analytical technique provided detailed insights into the wire's thermal behavior and durability over repeated exposures. The TGA graph exhibited a consistent and notable increase in weight loss with each subsequent cycle. This weight loss, attributed to material degradation or loss, indicated a diminishing structural integrity of the SMA wire. Moreover, the graph pinpointed the specific temperature at which significant degradation commenced, offering a critical understanding of the thermal threshold beyond which the wire's properties began to deteriorate markedly.

Analyzing the slope of the weight loss curve on the TGA graph allowed researchers to assess the rate of degradation. A steep slope indicated rapid deterioration, while a gentler slope suggested a slower decline in material properties over successive cycles of thermal stress [17]. Furthermore, the TGA analysis culminated in the identification of an endpoint where weight loss stabilized, signaling that the SMA wire had reached a state of reduced stability and diminished performance. This stabilization point served as a practical indicator of the wire's limitations under repeated thermal exposures.

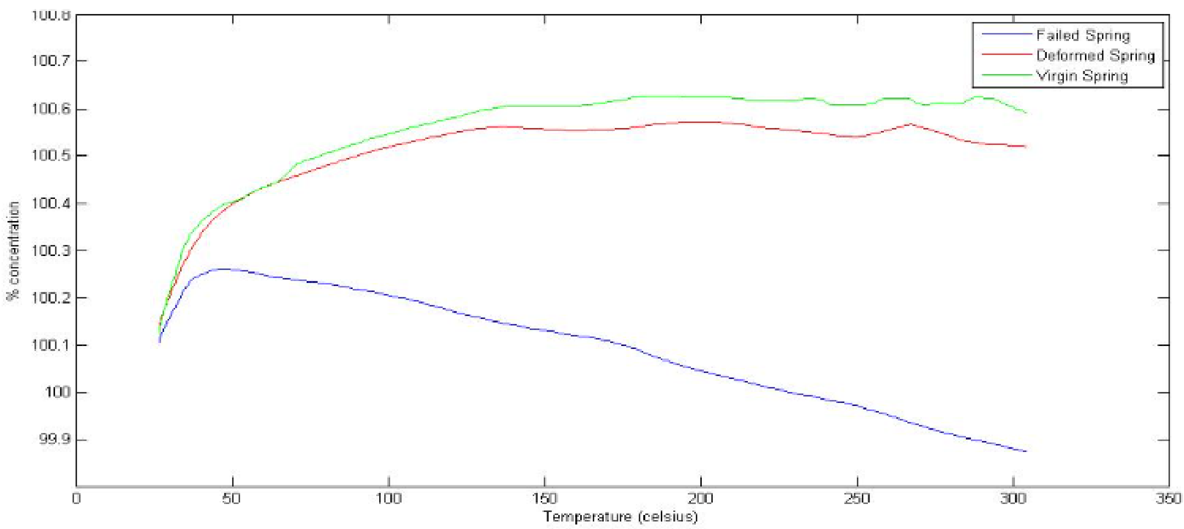


Fig. 4.7 TGA graph

Conclusion:

After the completion of this review, we were able to gain a comprehensive understanding of the utilization of Shape Memory Alloys (SMAs) in biomedical applications, expanding our knowledge on how these materials can revolutionize various aspects of healthcare delivery.

- Our exploration of the fundamental principles and mechanical properties of SMAs provided insights into their potential for creating tailored implants that can enhance patient outcomes and reduce the need for additional surgeries.
- By discussing the challenges associated with integrating SMAs into biomedical devices, we identified areas for further research and development, paving the way for innovations that can address current limitations.
- The examination of specific biomedical applications, recent advancements, and emerging trends in the field allowed us to envision future possibilities where SMAs play a central role in improving healthcare standards and patient experiences.
- Through mechanical testing of NiTi alloys under controlled conditions, such as water baths and electrical loads, we not only validated their reliability but also contributed valuable data for optimizing their performance in real-world medical scenarios.

This review paper serves as a comprehensive resource for researchers, engineers, and healthcare professionals, fostering collaboration and driving progress towards leveraging SMAs for transformative advancements in biomedical engineering.

Future Scope:

In the realm of smart implants, the focus can be on integrating sensors and actuators into Shape Memory Alloys (SMAs) to create intelligent implants that respond to physiological signals or external triggers. These "smart" implants have the potential to dynamically adjust their properties, such as shape or stiffness, in real-time. This adaptability can optimize therapeutic outcomes and enhance patient comfort by tailoring the implant's behaviour to specific conditions or activities.

Another promising avenue could be exploring SMAs' role in tissue regeneration. Beyond supporting tissue structures, SMAs may actively contribute to tissue repair and regeneration processes. By understanding how SMAs interact with biological systems, researchers can investigate their ability to stimulate cell growth, facilitate tissue remodelling, and accelerate wound healing. These efforts can lead to improved patient outcomes, reduced recovery times, and enhanced functionality of tissue-engineered constructs or implants.

Additionally, the integration of nanotechnology into SMAs opens up exciting possibilities. Nanoscale modifications can enhance SMA properties, such as improving biocompatibility, mitigating corrosion risks, or enabling precise drug delivery from implant surfaces. By harnessing nanotechnology, researchers can fine-tune the performance and functionality of SMAs, paving the way for more effective and durable medical implants with tailored therapeutic capabilities.

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