Journal of Physical Chemistry and Functional Materials

Home Page of Journal: https://dergipark.org.tr/jphcfum

A Review on Comparison between NiTi-Based and Cu-Based Shape Memory Alloys

[a]Belan Mohammed IBRAHIM, [a]Safar Saeed MOHAMMED*, [b]Esra BALCI

[a]*Department of Physics, College of Science, University of Raparin, Ranya, Sulaymaniyah-Iraq*
[b]*Inonu Univercity, department of physics, Malatya, Turkey.*
**corresponding author:* Safar Saeed MOHAMMED *(email: safar.saeed@uor.edu.krd)*

ABSTRACT

One of the best types of smart materials is Shape Memory Alloys (SMAs), which have more applications in modern technology such as aerospace, automotive, biomedical, civil engineering, robotics, and so on. Among all parts of them NiTi-based, and Cu–based are more focused on because they have some interesting properties that have made them more widely used in modern technology. There are more works in the literature on each of these two types of shape memory alloys, but the distinctive and important point of this work compared to other works is that this work has focused on the comparison between these two types. In this work, the classifications and applications of SMAs according to the different application fields like biomedical, automotive, and aerospace have been reviewed. Besides the characteristics of (NiTi-based, and Cu-based) and the comparison between them in many areas such as: In terms of cost, creation, corrosion resistivity, density, and electrical and thermal conductivity were represented. Each of NiTi and Cu-based SMAs has many useful applications and strengths, but they have some limitations.

ARTICLE INFO

Keywords:
NiTi-based SMA
Cu-based SMA
shape memory alloy
Comparison between NiTi-based and Cu-based SMAs
shape memory effect
superelasticity.

Received: 2023-09-09
Accepted: 2023-11-01
ISSN: 2651-3080
DOI: 10.54565/jphcfum.1357636

1. INTRODUCTION

The development of modern technology depends on the fundamental materials used in it. Many different types of materials are useful for the development of technology. One of these groups is smart materials which are known to have many unique behaviours compared to other types of materials [1, 2].

Smart materials are divided into several groups of materials. Shape memory alloys (SMAs) are a special type of smart material which can keep their previous shape in mind after thermo-mechanical loads have plastically deformed them [3, 4]. These alloys in deformed shapes undergo a kind of solid-to-solid phase transformation, by heating, which leads them to reverse their original shape without applying any load. The change between one type to another type of crystalline structure produces the mechanism by which shape modification happens in SMAs. This transformation contains the conversion from a cubic crystal form (austenite) to a monoclinic form (martensite) [5]. A martensitic transformation that occurs as austenite ↔ martensite (A↔M) inter-transition is the underlying mechanism responsible for interesting characteristics of SMAs, for example, pseudoelasticity (superelasticity), and shape memory effect (SME) properties. Many alloys own a special characteristic to these transforming such as Fe, Cu, and NiTi-based SMAs. SMAs have two various phases and three various crystal structures (i.e. austenite, (detwinned and twinned) and martensite)) [6, 7]. The martensite structure and austenite structure are stables at low temperatures and higher temperatures respectively.

In this review, an attempt has been made to clarify the definition of shape memory alloy materials, as well as their fundamental and unique properties.

Their different types and technological applications are highlighted and finally, a comparison is made between Niti-based and Cu-based in terms of their physical and chemical properties.

2. SHAPE MEMORY ALLOYS (SMAS) OVERVIEW

Shape memory alloys (SMAs) are a class of metal alloys that, when subjected to a stimulus like heat energy, magnetic field, can revert to their previous shape after phase transformation process between two phases. These alloys often have two main features: the first is the shape memory effect (SME), which occurs in a temperature gradient, and the second is pseudoelasticity, an isothermal phenomenon.

SMAs are therefore described as metallic materials that can take on their original form when the proper temperature conditions are applied. As a result, their demand has expanded in a variety of applications due to their appealing properties.[8].

2.1. Shape Memory Effect (SME)

As mentioned before SMAs have two main crystal structure (austenite and martensite). When the martensite (low-temperature phase) is converted into (high-temperature phase) austenite by an external load, and after heating it can remind the previous phase (martensite), this phenomenon is called shape memory effect (SME) [9].

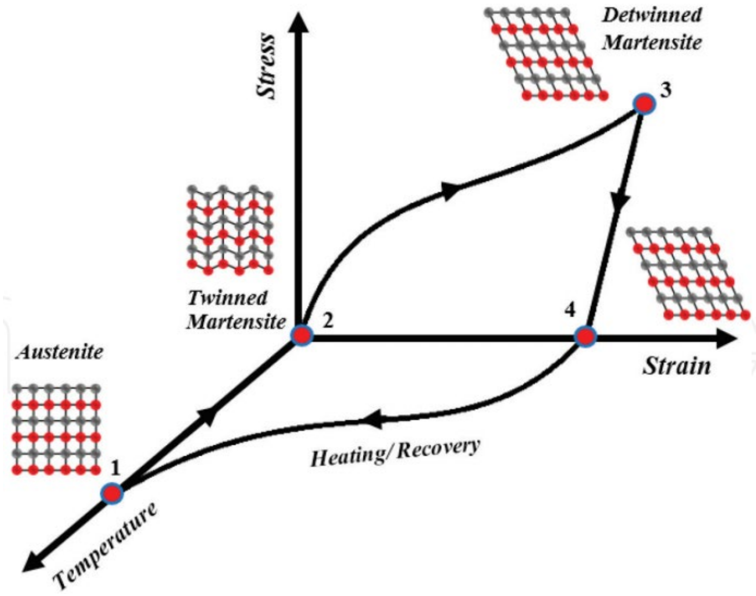

Figure 1. Schematic diagram of SME [9, 10]

The SME schematically was demonstrated in Figure 1 during the cyclic process (1→2→3→4→1) in the stress-strain-temperature diagram [9]. When the alloy at the austenite phase cooled the transformation started at a martensite start temperature (M_s), and at a martensite finish temperature (M_f) the phase converted into twinned martensite during (1→2) process, and after adding an external stress on twinned martensite the structure of alloy changed into detwinned martensite through (2→3) process. And after removing the external stress the structure does not change during the (3→4) process. But in the (4→1) process, the detwinned martensite phase recovered to the permanent phase (austenite) after being heated [9].

There are two different types of SME, which are the one-way shape memory effect (OWSME) and the two-way shape memory effect (TWSME). Figure 2. explains both of them. According to Figure 2-a, after heating the alloy can return to its previous state directly, this is OWSME, and Figure 2-b shows TWSME which in the alloy has both martensite and austenite phase, but the ability of OWSME is greater than TWSME to recovery strain.[11].

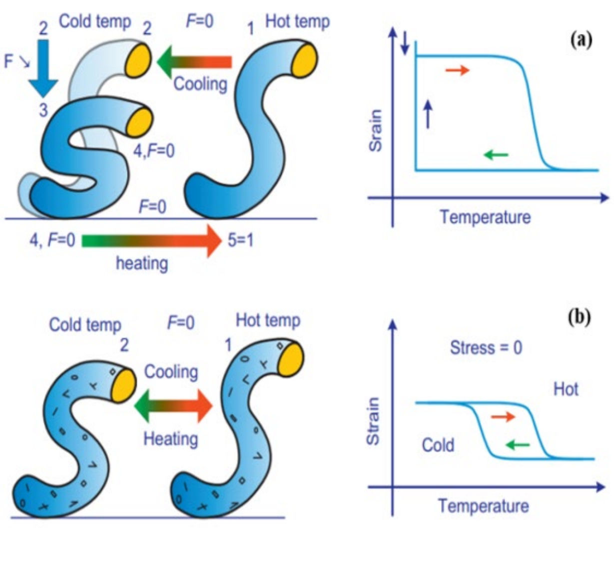

Figure 2. shape memory effect (a) One-way, (b) Two-way [12]

2.2. Pseudoelasticity

Another useful behaviour of SMA is pseudoelastic (superelasticity) for lots of applications. Pseudoelasticity, unlike the (SME), happens in a small temperature range above the Austenite finish (A_f), where the stress on shape memory alloys increases, the microstructures (crystal structure), and therefore macroscopic shape deforms, both of them can recover to their original shape after decreasing the load [4, 13].

Pseudoelasticity has two sorts of crystal structure; unload state is austenite cubic crystal structure and the load state is detwinned martensite structure, When loaded at a high temperature greater than the Austenite finish (A_f), a macroscopic deformation happens due to that crystal structure changes microscopically from cubic to detwinned martensite phase and after then by decreasing load or stress the crystal structure changes to austenite phase again which leads macroscopic shape return to the original shapes, as shown in Figure 3 [14-16].

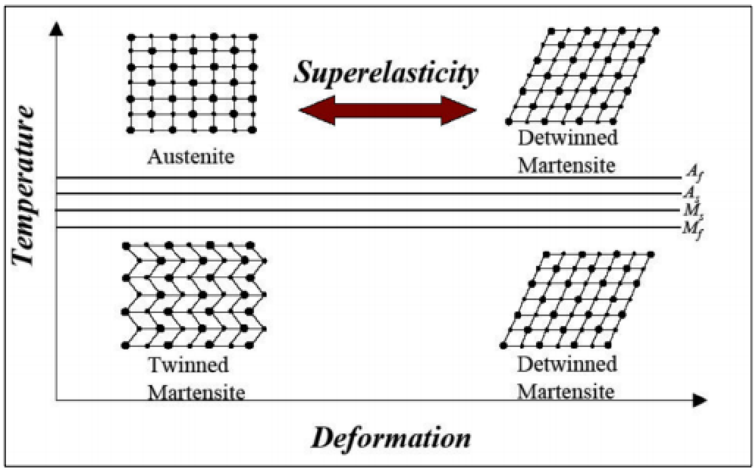

Figure 3. Pseudoelasticity behaviour of shape memory alloys [16].

3. COMPARISON BETWEEN NITI-BASED AND CU-BASED SMAS AND THEIR TECHNOLOGICAL

Shape memory alloys comprising various metal components are generally categorized according to the main most (the most elevated rate) constituting element or binary elements in the SMA systems. SMAs are chosen to be utilized in applications depending on their requested properties, processability, costs, biocompatibility, usefulness, etc. Metallic material SMAs can be classified into six categories of alloys that illustrate SME in a binary system with another component being added, Cu-based, Ag-based, NiTi-based, Fe-based, Co-based alloys, and Au-based. Each of them has a special property of SME and they can change the properties by modifying the composition and by adding or making ternary and quaternary alloys and changing the proportion of composition [8, 17]. But three basses are rife and have good SME properties which are Fe, Cu, and NiTi-based (SMAs) [18]. Also, Cu-based, and NiTi-based have more technological applications.

3.1. Nickel – Titanium Alloys

In 1962, the NiTi SMA was first discovered and was called NiTinol at that time. It is (NiTi) a classic SMA in terms of heat recoverability (8%) [19, 20]. Their remarkable properties (e.g., SME and SE of the NiTi alloy) have found uses in a lot of sectors of manufacturing [21, 22]. Due to thermal treatment and external stress (martensite, B19' monoclinic phase ↔ austenite, B2 cubic phase), SMEs derive from martensitic and reverse martensitic transformations. [23]. The temperature that is needed to occur the phase change thus leading the memory effect to take place can be adjusted from -200°C to 100°C by the amount of titanium and nickel around the equiatomic ratio of 45 wt.% Ti and 55 wt.% Ni and by addition of other elements, the temperature for phase transformation can alter by 20°C or more by changing only 0.1 (at.%) of compositions [24, 25] therefore, all elements of NiTi alloy are sensitive and need to be carefully changed. This sensitivity is decreased by the addition of copper into NiTi. The production and melting of Nickel-Titanium and the presentation of conventional titanium alloy manufacture are expensive due to titanium can easily oxidate [26-28].

3.2. Copper – Based Shape Memory Alloys

Cu-based SMA development has decreased many of the NiTi alloy problems [19]. Due to their relatively low costs, ease of manufacturing, and High electrical and thermal conductivity, copper-based SMAs offer advantages and extension of applications. Fabrication of memory alloys based on copper is created simply by melting the pure materials, however, melting loss of volatile elements must be taken into account in the fabrication process and certain alloy composition is needed to control transformation temperatures[29].

Cu-based SMAs have three binary alloys : (Cu-Sn, Cu-Zn, and Cu-Al) as they are shown in Table 1 of Cu-based SMAs in Figure 5 [30, 31]. To change and enhance the good properties of binary SMAs one or more extra additive elements are added to produce ternary and quaternary SMAs.

Table 1. Types of Cu-based SMAs[32], where Y(g) is an element used to refine grains, such as B, Ce, Co, Ti, V, or Zr.

	Cu_based SMA		
	Cu Zn	Cu Al	Cu-Sn
Addition third element	Cu Zn-X X= Ga, Al, Si, Mn, Sn	Cu Al X X= Mn, Ni, Zn, Be	Cu Sn X X= Mn, AL
Adding fourth element	Cu Zn Al Ni Cu Zn Al Mn	Cu Al Ni Mn	
industrial alloys	Cu Zn Al Y(g) Cu Zn AL Mn-Y(g)	Cu- Al Ni Y(g) Cu Al Ni Mn-Y(g)	

3.3. Applications of NiTi-based and Cu-based SMAs.

In today's world of modern technology, smart materials have absolute dominance in advancing the world of technology. Shape memory alloys, which are a special group of smart materials, play an important role in technology depending on their unique behaviours (shape memory effect and superelasticity), and they have more applications in many fields such as biomedical, aerospace, automotive, and robotic.

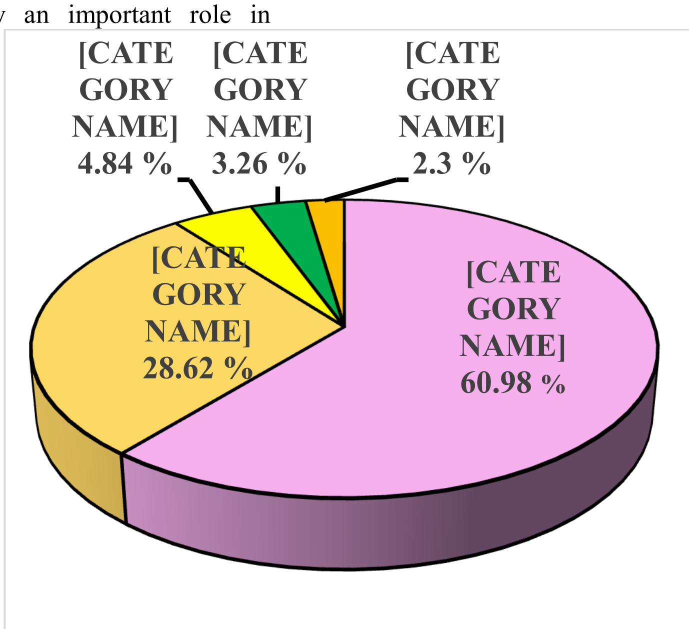

Figure 4. Pie chart showing the patent area of SMAs during 1990-2013 [8].

The pie chart is given in Figure 4. Shows the patent area of SMAs between 1990 - 2013. In this work, some of the important applications of SMAs especially Cu-based and NiTi-based have been explained. In addition to their specific characteristics (superelasticity and the shape memory effect), they also exhibit certain additional fascinating features that support their usage in medical applications [33].

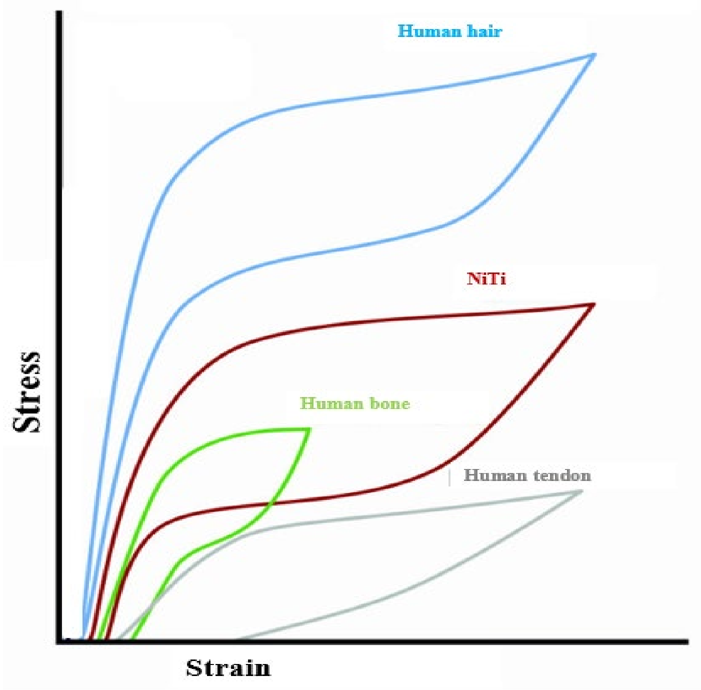

Figure 5. Comparison between the behaviour of NiTi with some living tissues due to the stress-strain [34]

3.3.1. Biomedical Applications

The capability of materials to reveal their behaviour with live organs in the human body without causing any harm is known as biocompatibility [35, 36]. Because of excellent biocompatibility [37, 38] and large strain recovery, which is roughly (8%) compared to Cu-based (5%)[39], which is larger than the strain recovery of tissues and bones (Figure 5), NiTi alloys have more medical uses than Cu-based alloys. Additionally, NiTi SMA is more corrosion resistant than Cu-alloy, and although titanium is non-toxic and nickel is very toxic, Due to the titanium oxide layer (TiO2) in front of the nickel leaking acts as a physical barrier, the alloy is frequently protected from oxidation.

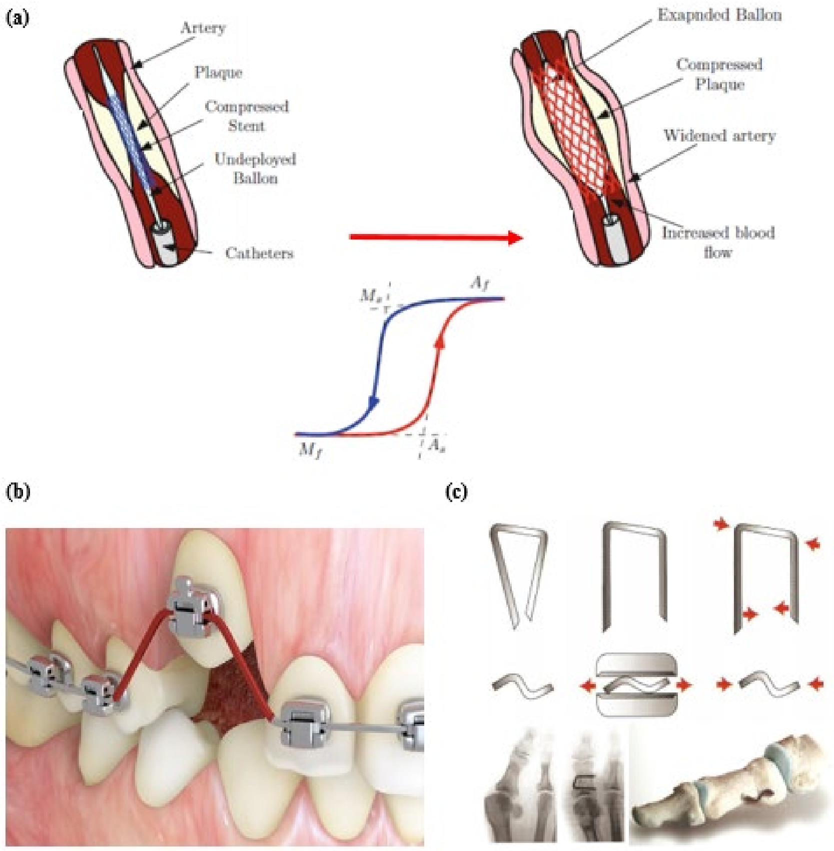

Figure 6. Some applications of SMA in (a) opening the blocked nerves, (b) orthodontic, and (c) orthopaedic [40, 41].

NiTi SMA has several medical applications, such as enhancing blood flow in blocked nerves, orthopaedic [40], and orthodontic [41, 42], because of biocompatibility and its better shape memory. Figure 6-a illustrates the setting of NiTi SMA in the blocked region of the nerves to apply SME of NiTi for opening the blocked nerves. It undergoes compression in the first stage before being implanted in the nerve by an applied force into the martensite phase. The alloy is then heated in the nerve to transform it into an austenite phase. The SE use of SMA in both orthopaedics and orthodontics is shown in Figures 6-b and -c. The SMA-based wire changes shape when stretched, and after being fixed to the teeth and cracked bone during the recovery process, it returns to its previous state. During the recovery phase, the orthopaedic wire may coincide with the teeth (in orthodontics) [40, 41].

3.3.2. Aerospace Applications

SMAs are used increasingly often in aircraft as actuators, connectors, vibration dampers, manipulators, and pathfinder applications because of their distinctive features, which also allow them to resist high dynamic pressure and geometric restrictions on space.[43-46]. Figure 7 displays a telescoping wing system as an illustration of SMA uses in aerospace applications

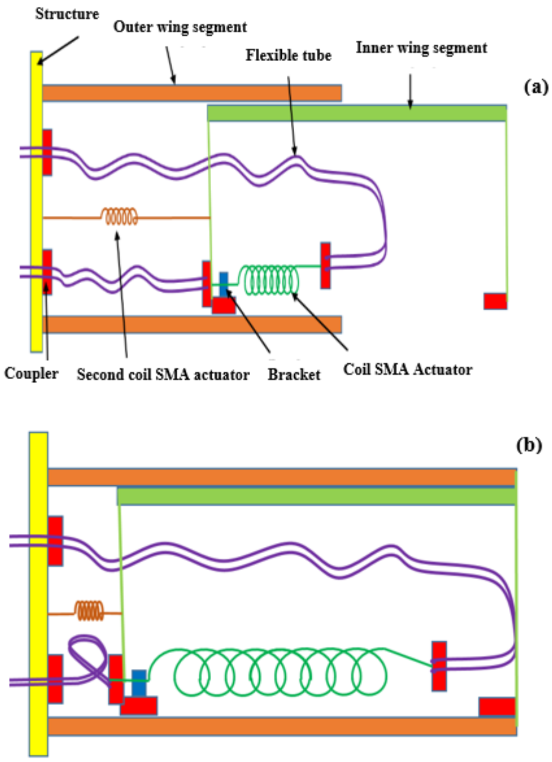

Figure 7. Telescopic flap mechanism (a) when the center segment retracted as the helical SMA actuator cooled (b) when the center segment extended after the helical SMA actuator heated [47].

Figure 7 illustrates a telescoping wing system as an example of SMA used in the aerospace industry [5]. An actuator spreads out two inner and outer segments. It is based on an SMA coil that has been shaped into a tube. The coil compresses and martensite phase changed to austenite when it heated. The second coil returned the center segment by a cooled SMA helical actuator since its phase has returned to martensite (Figure 7-b), and the compressed SMA connects the inner and outer segments (Figure 7-a).[47]

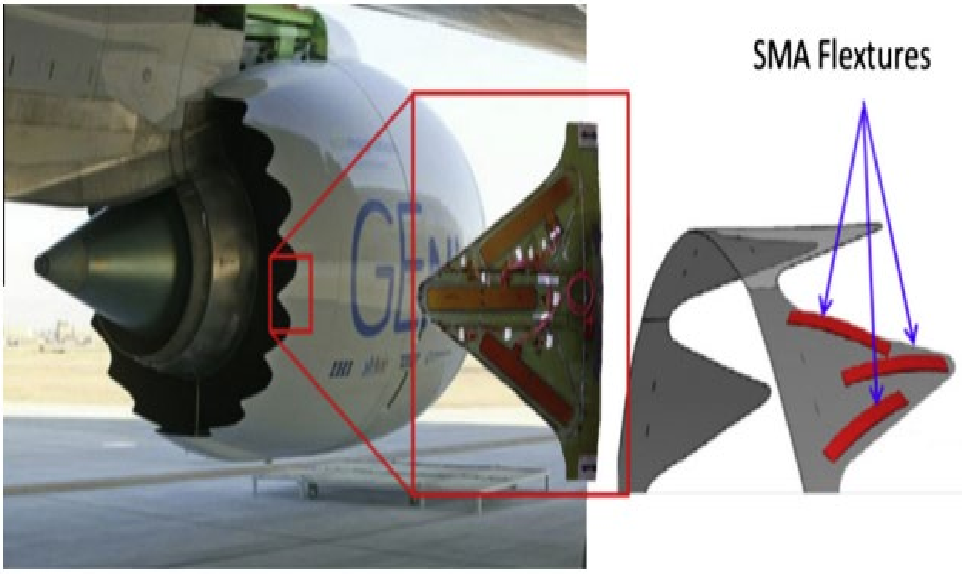

Figure 8. Boing aircraft which used SMA in it [48]

The variable geometry chevron (VGC), also known as an aerodynamic serrated system, was created by The Boeing Company which uses SMA as an actuator (Figure 8). By maximising chevron deviation, this technique is highly effective in reducing and decreasing engine noise while the aircraft is in flight. Additionally, the SMA-based actuator at the Ge90-115B jet engine boosts cruise efficiency by reducing chevron deflection during the remaining flight. [48]. However, they ran into trouble as the temperature inside increased due to exhaust. This issue was overcome by the NASA Glenn Research Centre employing actuators made of high-temperature shape memory alloy (HTSMA). Both Cu-based and NiTi-based SMAs are more used in aerospace technology Because their properties are better than other types of alloys for use in this type of technology.[49].

3.3.3. Automotive Applications

To increase passenger safety and comfort, current automobile designers are working to develop cars with more automated and advanced motors. The number of micro collectors, actuators, and sensors has been increased to achieve this target; nevertheless, these extra components raise the car's total weight, volume, and cost. As a result, they are trying to solve these issues by using specific materials like SMA, (Figure 9). SMAs may be used as an actuator or sensors and offer relatively high actuation force and output power per volume. [50]. Additionally, because of their outstanding mechanical characteristics, NiTi-based and cu-based alloys are more practical and have more automotive applications than other forms of SMAs. [51-53].

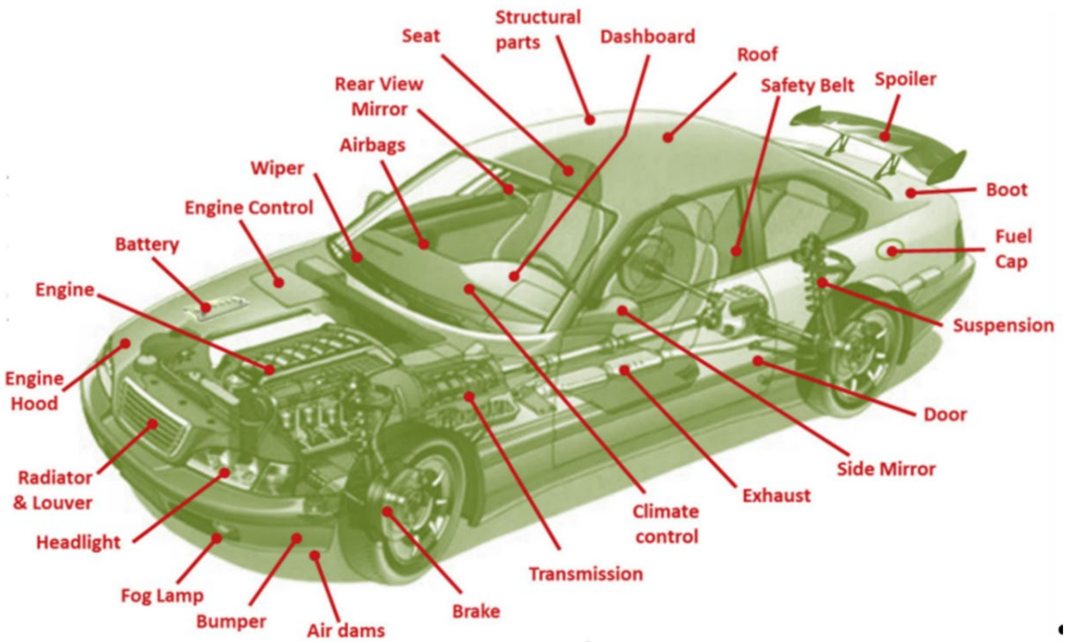

Figure 9. Automotive parts based on SMA-actuators [11]

Because the temperature range in the passenger room is (-40°C to +85 °C) and the transformation temperature of NiTi alloy is -50 °C to +110 °C, therefore the NiTi SMA is the best option to use in it; however, it cannot be used in the engine room because its operating temperature range is between (-40 °C and +125 °C). Therefore, due to its transformation temperature range of (-200 0C to 200 0C), the Cu-based alloy can be used in engine rooms[54]. A thermostatic radiator control is another spring actuator made by SME (Figure 10). The actuator expands as an engine temperature rises, overpowering the bias spring's force to close the valve hole on the radiator system's hot water line. Cu-based alloy is better appropriate for this purpose than NiTi alloy due to its higher thermal conductivity. [55] (The NiTi thermal conductivity of the austenite phase is (18 w/ (cm. 0C)) while that of the martensite phase is (8.5 w/ (cm. 0C)) [56]. And the Cu-based austenite phase's thermal conductivity ranged between (79-120 w/ (cm. 0C) [24].

Figure 10. The thermostatic radiator valve is produced based on a Cu-based alloy actuator spring [55].

Another automotive component that needs high thermal conductivity material is a clutch fan (Figure 11), which employs a Cu-based SME actuator in the form of a spiral spring that is biassed towards a collection of four metal leaf springs. The SME actuator coil activates a clutch that powers an automobile engine fan when the "air-off" temperature climbs beyond a certain threshold, typically 53°C; the actuator then closes the clutch plate after controlled temperature.

Figure 11. clutch fan actuator constructed of Cu-based alloy [55]

The fan idles at -250 revs when the temperature is low. In order to cool the engine unit at greater temperatures, the clutch fan speeds faster. If this speed is slower than the vehicle's speed, the clutch will turn on. [55].

4. CONCLUSION

One of the best types of smart materials is Shape Memory Alloys (SMAs), which have more applications in modern technology, and so on. Among all parts of them NiTi-based, and Cu–based are more focused on because they have some interesting properties that have made them more widely used in modern technology.

In this work, the compression between the Cu-base and NiTi base of SMAs has been revised based on the application of each in different areas of modern technology. The comparison between both of them is summarized below:

- The NiTi-based alloy has 6–8% recoverable strain [57]. And it is more than the Cu-based recoverable strain which is about 5% [58].
- The fabrication and melting of Nickel-Titanium and the presentation of conventional titanium alloy manufacture are costly because titanium can easily oxidise [26]. While Cu-based is easy to fabricate and has cheaper production costs than NiTi [59]. And since they are simply manufactured using conventional and powder metallurgy routes, and liquid metallurgy used for processing typical Cu-based alloys, they are considered cost-effective [30].
- NiTi-based SMAs have great pliancy, and perfect corrosion resistance in different environments containing excel in low cycle fatigue, body fluids, and strain-controlled environments [57]. Cu-based alloys often have low strength and poor corrosion resistance. [24, 60]. Despite these NiTi properties, commercial applications are restricted due to expensive costs and the difficulty of production [61].
- The Cu-based alloy phase transformation temperature is between (-200 ^{0}C to 200 ^{0}C) and it is wider than the range NiTi phase transformation which is changed from -200 ^{0}C to 100 ^{0}C by some recommended methods [60].
- The density of Cu-based is equal to (7.64 g.cm^3) [62]. and it is denser than the NiTi alloys which are equal to (6.45 g.cm^3) [56].
- The NiTi Electrical resistivity of the austenite phase (≈ 100 μΩ cm) and it is (≈70 μΩ cm) for the martensite phase, [56]. Which is greater than the Cu-based it's (7, 14 μΩ cm) for both the austenite phase and martensite phase respectively, [24].
- The NiTi thermal conductivity austenite phase is (≈ 18 w/ (cm. ^{0}C)) and it (≈ 8.5 w/ (cm. ^{0}C)) for martensite [56]. And the thermal conductivity for the Cu-based austenite phase spanned (79-120 w/ (cm. ^{0}C) [24].

REFERENCES

[1] F. Dagdelen, E. Balci, I. Qader, E. Ozen, M. Kok, M. Kanca, S. Abdullah and S. Mohammed. Influence of the Nb content on the microstructure and phase transformation properties of NiTiNb shape memory alloys. *JOM*. 2020;72:1664-1672.

[2] M. Kök, I. N. Qader, S. S. Mohammed, E. Öner, F. Dağdelen and Y. Aydogdu. Thermal stability and some thermodynamics analysis of heat treated quaternary CuAlNiTa shape memory alloy. *Materials Research Express*. 2019;7(1):015702.

[3] S. S. Mohammed, M. Kok, I. N. Qader, M. S. Kanca, E. Ercan, F. Dağdelen and Y. Aydoğdu. Influence of Ta Additive into Cu 84− x Al 13 Ni 3 (wt%) Shape Memory Alloy Produced by Induction Melting. *Iranian Journal of Science and Technology, Transactions A: Science*. 2020;44:1167-1175.

[4] I. N. Qader, E. Öner, M. Kok, S. S. Mohammed, F. Dağdelen, M. S. Kanca and Y. Aydoğdu. Mechanical and Thermal Behavior of Cu 84− x Al 13 Ni 3 Hf x Shape Memory Alloys. *Iranian Journal of Science and Technology, Transactions A: Science*. 2021;45:343-349.

[5] J. F. Wakjira. The VT1 shape memory alloy heat engine design: Virginia Tech; 2001.

[6] I. J. P. P. M. E. Mihálcz. Fundamental characteristics and design method for nickel-titanium shape memory alloy. 2001;45(1):75-86.

[7] S. S. Mohammed, K. Mediha, I. QADER and R. QADIR. A Review on the Effect of Mechanical and Thermal Treatment Techniques on Shape Memory Alloys. *Journal of Physical Chemistry and Functional Materials*.5(1):51-61.

[8] J. M. Jani, M. Leary, A. Subic, M. A. J. M. Gibson and Design. A review of shape memory alloy research, applications and opportunities. 2014;56:1078-1113.

[9] D. C. Lagoudas. Shape memory alloys: modeling and engineering applications. Springer; 2008.

[10] S. S. M. Mohammed. Production and investigation of some physical properties of CuAlNiTa quaternary shape memory alloys: Fen Bilimleri Enstitüsü; 2021.

[11] J. M. Jani, M. Leary, A. Subic and M. A. Gibson. A review of shape memory alloy research, applications and opportunities. *Materials & Design (1980-2015)*. 2014;56:1078-1113.

[12] A. Ziolkowski. Pseudoelasticity of shape memory alloys: theory and experimental studies. Butterworth-Heinemann; 2015.

[13] B. Mellor, J. Guilemany and J. J. L. J. d. P. I. Fernandez. Two way shape memory effect obtained by stabilised stress induced martensite in Cu-Zn-Al-Co and Cu-Al-Mn alloys. 1991;1(C4):C4-457-C4-462.

[14] V. B. Krishnan. Design, fabrication and testing of a shape memory alloy based cryogenic thermal conduction switch. 2004.

[15] A. Czechowicz and S. Langbein. Shape memory alloy valves: Basics, potentials, design. Springer; 2015.

[16] M. MEHRPOUYA. MODELING OF MACHINING PROCESS OF NICKEL-TITANIUM BASED SHAPE MEMORY ALLOY: Department of Mechanical and Manufacturing Engineering, Faculty of …; 2013.

[17] S. S. Mohammed, K. Mediha, I. N. Qader and F. Dağdelen. The Developments of piezoelectric Materials and Shape Memory Alloys in Robotic Actuator. *Avrupa Bilim ve Teknoloji Dergisi*. 2019(17):1014-1030.

[18] K. Otsuka and C. M. Wayman. Shape memory materials. Cambridge university press; 1999.

[19] E. Noyan. Shape memory alloy design. 1990.

[20] C. Laureanda. One Way and Two Way–Shape Memory Effect: Thermo–Mechanical Characterization of Ni–Ti wires: Ph. D. thesis, Universitá degli Studi di Pavia; 2008.

[21] H. Kahn, M. Huff, A. J. J. o. M. Heuer and Microengineering. The TiNi shape-memory alloy and its applications for MEMS. 1998;8(3):213.

[22] L. Petrini and F. J. J. o. M. Migliavacca. Biomedical applications of shape memory alloys. 2011;2011.

[23] E. M. SHARIFI and A. J. T. o. N. M. S. o. C. Kermanpur. Superelastic properties of nanocrystalline NiTi shape memory alloy produced by thermomechanical processing. 2018;28(3):515-523.

[24] K. Worden, W. A. Bullough and J. Haywood. Smart technologies. World Scientific; 2003.

[25] R. QADIR, S. MOHAMMED, K. Mediha and I. QADER. A Review on NiTiCu Shape Memory Alloys: Manufacturing and Characterizations. *Journal of Physical Chemistry and Functional Materials*. 2021;4(2):49-56.

[26] D. C. Acitei, A. V. Sandhu, M. M. A. B. Abdullah, P. Vizureanu and A. Abdullah, editors. On the structure of shape memory alloys. Key Engineering Materials; 2014: Trans Tech Publ.

[27] S. MOHAMMED, K. Mediha, I. N. Qader and M. Coşkun. A Review Study on Biocompatible Improvements of NiTi-based Shape Memory Alloys. *International Journal of Innovative Engineering Applications*. 2021;5(2):125-130.

[28] S. S. Mohammed, E. Balci, H. A. Qadir, I. N. Qader, S. Saydam and F. Dagdelen. The exploring microstructural, caloric, and corrosion behavior of NiTiNb shape-memory alloys. *Journal of Thermal Analysis and Calorimetry*. 2022;147(21):11705-11713.

[29] S. Mohammed, M. Kök, Z. Çirak, I. Qader, F. Dağdelen and H. S. Zardawi. The relationship between cobalt amount and oxidation parameters in NiTiCo shape memory alloys. *Physics of Metals and Metallography*. 2020;121:1411-1417.

[30] R. J. J. o. M. R. Dasgupta. A look into Cu-based shape memory alloys: Present scenario and future prospects. 2014;29(16):1681.

[31] M. Kok, R. A. Qadir, S. S. Mohammed and I. N. Qader. Effect of transition metals (Zr and Hf) on microstructure, thermodynamic parameters, electrical resistivity, and magnetization of CuAlMn-based shape memory alloy. *The European Physical Journal Plus*. 2022;137(1):62.

[32] R. Dasgupta. A look into Cu-based shape memory alloys: Present scenario and future prospects. *Journal of Materials Research*. 2014;29(16):1681-1698.

[33] E. Ercan, F. Dagdelen and I. Qader. Effect of tantalum contents on transformation temperatures, thermal behaviors and microstructure of CuAlTa HTSMAs. *Journal of Thermal Analysis and Calorimetry*. 2020;139(1):29-36.

[34] S. A. Shabalovskaya. On the nature of the biocompatibility and on medical applications of NiTi shape memory and superelastic alloys. *Bio-medical materials and engineering*. 1996;6(4):267-289.

[35] B. D. Ratner. The biocompatibility manifesto: biocompatibility for the twenty-first century. *Journal of cardiovascular translational research*. 2011;4(5):523-527.

[36] E. Balci, F. Dagdelen, S. Mohammed and E. Ercan. Corrosion behavior and thermal cycle stability of TiNiTa shape memory alloy. *Journal of Thermal Analysis and Calorimetry*. 2022:1-8.

[37] R. Dutta, K. Madangopal, H. Gadiyar and S. Banerjee. Biocompatibility of Ni–Ti shape memory alloy. *British Corrosion Journal*. 1993;28(3):217-221.

[38] S. MOHAMMED, F. DAĞDELEN and I. N. QADER. Effect of Ta Content on Microstructure and Phase Transformation Temperatures of Ti75. 5-Nb25. 5 (% at.) Alloy. *Gazi University Journal of Science*. 2022:1-1.

[39] S. Ashbli and C. Menzemer. On the Fatigue Behavior of Nanocrystalline NiTi Shape Memory Alloys: A Review. *J Nanomed Nanotechnol*. 2019;10(529):2.

[40] P. P. Poncet. Nitinol medical device design considerations. *Strain*. 2000;2(4):6.

[41] M. d. A. Ferreira, M. A. Luersen and P. C. Borges. Nickel-titanium alloys: A systematic review. *Dental Press Journal of Orthodontics*. 2012;17(3):71-82.

[42] S. Mohammed, E. Balci, F. Dagdelen and S. Saydam. Comparison of Thermodynamic Parameters and Corrosion Behaviors of Ti50Ni25Nb25 and Ti50Ni25Ta25 Shape Memory Alloys. *Physics of Metals and Metallography*. 2022;123(14):1427-1435.

[43] S. MOHAMMED, F. DAĞDELEN and I. N. QADER. Effect of Ta Content on Microstructure and Phase Transformation Temperatures of Ti75. 5-Nb25. 5 (% at.) Alloy. *Gazi University Journal of Science*.35(3):1129-1138.

[44] M. A. Cleveland. Apparatus and method for releaseably joining elements. Google Patents; 2008.

[45] H. Prahlad and I. Chopra, editors. Design of a variable twist tilt-rotor blade using shape memory alloy (SMA) actuators. Smart Structures and Materials 2001: Smart Structures and Integrated Systems; 2001: International Society for Optics and Photonics.

[46] G. A. Landis and P. P. Jenkins, editors. Dust on Mars: Materials adherence experiment results from Mars Pathfinder. Conference Record of the Twenty Sixth IEEE Photovoltaic Specialists Conference-1997; 1997: IEEE.

[47] G. Knowles and R. W. Bird. Telescopic wing system. Google Patents; 2004.

[48] D. Hartl, J. Mooney, D. Lagoudas, F. Calkins and J. Mabe. Use of a Ni60Ti shape memory alloy for active jet engine chevron application: II. Experimentally validated numerical analysis. *Smart Materials and Structures*. 2009;19(1):015021.

[49] R. D. Noebe, S. L. Draper, M. V. Nathal and A. Garg. High Work Output Ni-Ti-Pt High Temperature Shape Memory Alloys and associated Processing Methods. 2009.

[50] J. Huber, N. Fleck and M. Ashby. The selection of mechanical actuators based on performance indices. *Proceedings of the Royal Society of*

London. Series A: Mathematical, physical and engineering sciences. 1997;453(1965):2185-2205.
[51] K. E. Wilkes and P. K. Liaw. The fatigue behavior of shape-memory alloys. *JOM*. 2000;52(10):45-51.
[52] J. Cederström and J. Van Humbeeck. Relationship between shape memory material properties and applications. *Le Journal de Physique IV*. 1995;5(C2):C2-335-C2-341.
[53] W. J. Buehler and F. E. Wang. A summary of recent research on the nitinol alloys and their potential application in ocean engineering. *Ocean Engineering*. 1968;1(1):105-120.
[54] D. J. Leo, C. Weddle, G. Naganathan and S. J. Buckley, editors. Vehicular applications of smart material systems. Smart Structures and Materials 1998: Industrial and Commercial Applications of Smart Structures Technologies; 1998: International Society for Optics and Photonics.
[55] C. Wayman. Some applications of shape-memory alloys. *JOM*. 1980;32:129-137.
[56] D. J. M. s. T. Fugazza, University of Pavia, Pavia, Italy. Shape-memory alloy devices in earthquake engineering: mechanical properties, constitutive modelling and numerical simulations. 2003.
[57] T. Duerig and A. J. M. p. h. t. a. Pelton. Ti-Ni shape memory alloys. 1994;1:1035-1048.
[58] Y. Chen, X. Zhang, D. C. Dunand and C. A. J. A. P. L. Schuh. Shape memory and superelasticity in polycrystalline Cu–Al–Ni microwires. 2009;95(17):171906.
[59] M. Guerioune, Y. Amiour, W. Bounour, O. Guellati, A. Benaldjia, A. Amara, N. Chakri, M. Ali-Rachedi and D. J. I. J. o. S.-P. H.-T. S. Vrel. SHS of shape memory CuZnAl alloys. 2008;17(1):41-48.
[60] D. J. S. M. A. Cimprić, Univerza v Ljubljani, Fakulteta za matematikoin fiziko, Ljubljana. Seminarska naloga. 2007.
[61] K. K. Alaneme, E. A. J. E. S. Okotete and a. I. J. Technology. Reconciling viability and cost-effective shape memory alloy options–A review of copper and iron based shape memory metallic systems. 2016;19(3):1582-1592.
[62] B. Sun, J. Zhang, X. Wu and W. Liao, editors. Single-joint driving system of bionic finger based on shape memory alloy. 2012 International Symposium on Micro-NanoMechatronics and Human Science (MHS); 2012: IEEE.