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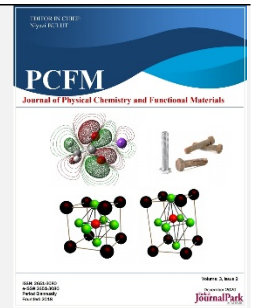

A Review on the Effect of Mechanical and Thermal Treatment Techniques on Shape Memory Alloys

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ABSTRACT

Despite many interesting behaviours and attractive properties of Shape memory alloys (SMAs), there are some drawbacks and limitations that prevent them from being used in technology. But some treatment techniques can be used to improve the behaviors of shape memory alloys. Also, they can remove or reduce the limitations of SMAs. In this study both mechanical treatment techniques (Ball- and Roller-Burnishing Treatment, Surface mechanical attrition treatment, and Laser shock peening) and heat treatment techniques (Annealing, Normalizing, Hardening, and Tempering) have been clarified. And the effect of both treatment techniques on the properties of shape memory alloys has been reviewed.

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1. Introduction

Recently smart materials are widely used in technological and industrial applications, among all types of them, shape memory alloys (SMAs) have been more utilized, because of their interesting properties such as shape memory effect (SME), superelastisity, biocompatibility, antirust, and so on [1-5]. Also in some applications, scientists and researchers try to improve some physical properties of memory alloy materials without changing the composition of elementary components by some techniques that are called treatment techniques. There are some different types of treatment techniques such as electromechanical treatment, chemical treatment, mechanical treatment, and thermal treatment. We try to annotate both mechanical and thermal treatment techniques.

In mechanical treatment, the alloy will be treated mechanically (without heating it) to improve some of its mechanical properties such as microhardness, as in Al-Qawabahs work showed that mechanical burnishing treatment caused to improve the microhardness of the Cu-Zn-Al shape memory alloy [6], and Hu et al. investigated that the wear resistance of NiTi SMAs was increased when it treated mechanically [7]. The mechanical treatment has some different types, but three types of them have more widely used for treating SMAs including burnishing, surface attrition and laser shot peening.

Also, heat treatment has four main types which are annealing, normalizing, hardening, and tempering. In this type of treatment technique, the treatment process will be performed on SMAs by two steeps which are heating and cooling [8]. Hence the temperature has a major role in the heat treatment process, and also in all types, the heating process is nearly the same that the specimen will be taken in the furnace during a time, but they are different in the cooling process, which we will discuss them in chapter three. And there is more research in the literature about the effect of heat treatment on the physical properties of shape memory alloys. Qader et al. studied the effect of heat treatment on microstructure and thermodynamics parameters of (Cu-Al-Ni-Hf) SMA, they found that Gibbs free energy and elastic energy were increased after treated it, while the microhardness was decreased [9], Chu et al. investigated the effect of heat treatment on ductility behaviour of porous Ni-rich NiTi shape memory alloy. They found that the treatment could improve the ductility of NiTi SMA [10]. Wang et al. studied the effect of annealing treatment on shape memory recovery of NiTi SMA, where they found that the shape memory recovery of the alloy was increased by increasing the annealing temperature [11].

In this study, both mechanical, and thermal treatment techniques and their branches have been investigated, and their effect on the microstructure and physical properties of SMAs were reviewed.

2. Shape Memory Alloys (Definition and Families)

Shape memory alloys (SMAs) are one group of smart materials, that have two main phases; the austenite phase which is the high-temperature solid solution phase, and the martensite phase which is a low-temperature phase and mechanically weaker than the austenite phase [3, 9, 12-14]. SMAs can change their phase between martensite and austenite phases through the heating/cooling process. This behavior of SMAs is called the shape memory effect (SME) [9, 12, 15-17]. Also, in a particular range of temperatures, the austenite phase can transform into an unstable martensite phase when an external load is applied to SMA, which is called pseudoelasticity (SE) (Figure 1) [12, 18-20]. SMAs can memorize their morphology and original shape when the effect of temperature and applied stress are cancelled.

SME has two main types, one-way shape memory effect (OWSME) and two-way shape memory effect (TWSME). In the first type, the alloy can return to its original state by heating, whereas in the second type, the SMA can be transformed into two different morphs: one in lower temperature and the other in the higher temperature phase (Figure 1).

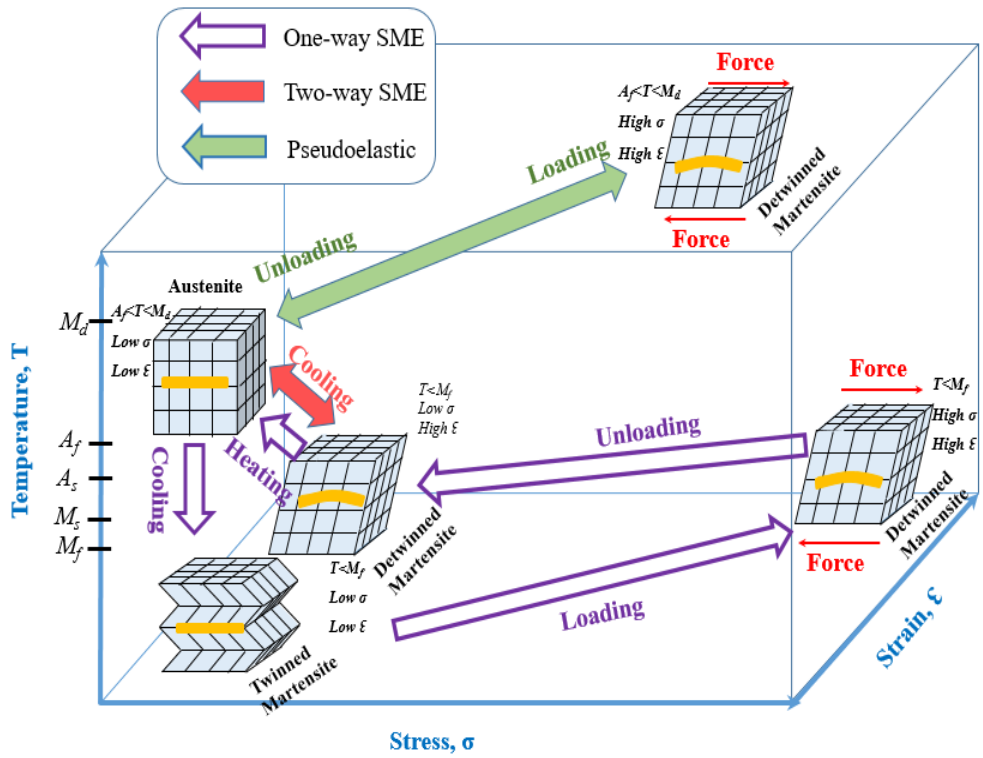

Figure 1. Schematic diagram of SMA phases and shape memory effect (SME) [12]

SMAs have several families such as Ag-Cd, Au-Cd, Cu-Al-Ni, Cu-Sn, Cu-Zn-(X), In-Ti, Ni-Al, Ni-Ti, Fe-Pt, Mn-Cu, and Fe-Mn-Si [16], however, three types of them, including nickel-titanium base, cupper-base, and iron-base, are more utilizing [21-24]. Particularly nickel-titanium (NiTi) is the standard choice for use in modern technology especially in medical applications because they have good biocompatibility [25, 26], ductility, antirust [27], much higher strength, larger recoverable strain, and most importantly higher reliability [28].

3. Treating Techniques

Shape memory alloys (SMAs) have more widely used in all technological applications, because of their interesting properties such as shape memory effect (SME) and superelastisity. But still, there are many obstacles in front of engineers to use these types of materials in different applications and a wide range of temperatures. Therefore, it has opened new gates of research for researchers to improve SMAs by applying techniques to treating them without changing their compositions.

There are two main treatment techniques commonly utilized for improving the SMA properties, including mechanical treatment, and thermal (heat) treatments. Some physical properties, such as mechanical characteristics, can be monitored after applying these treatments to the material. It should be kept in mind that these treatments do not work the same for all materials and the condition depends on several complex parameters.

3.1. Mechanical Treatment

Mechanical treatment is a technique to improve the properties of SMAs, such as fatigue life, roughness, microhardness, tensile strength, and corrosion resistance. The treatment process should be performed mechanically (not using heat or changing temperature). There are some known types of mechanical treatment for SMAs, which will be discussed in this section. The three main processes of them that have more use in modern technology and industry are burnishing, surface attrition and laser shot peening.

3.1.1. Ball- and Roller-Burnishing Treatment

Burnishing is one type of mechanical heat treatment of SMAs, in which the specimen is deformed plastically in its surface layer by a hardball or roller. Figure 2 presents the burnishing treatment process, where either ball or roller was pressed into the surface of the specimen by the burnishing force. The surface of the specimen is deformed permanently, and valleys are filled by erosion of the peaks.

According to the published reports in the literature, burnishing treatment can improve surface quality. Al-Qawabah found that roller burnishing treatment refines the roughness and microhardness of the Cu-Zn-Al shape memory alloy [6]. Likewise, Basak et al. showed that the burnishing mechanical treatment had a positive effect on surface hardness, wear resistance, and surface roughness of treated specimens [37].

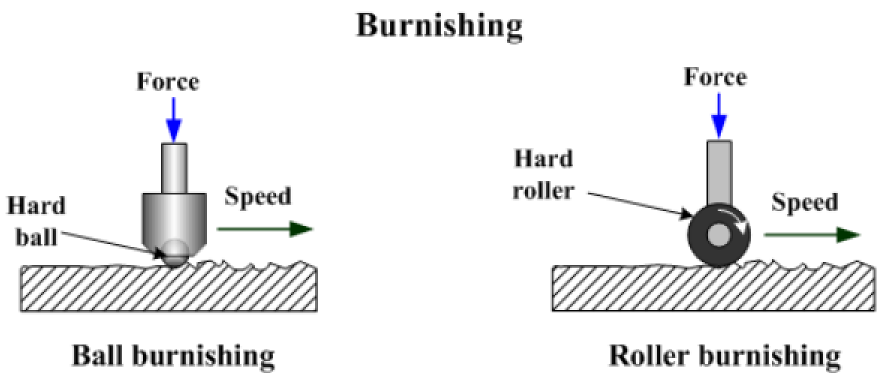

Figure 2 Experimental set-up for burnishing treatment [38]

3.1.2. Surface mechanical attrition treatment

In the surface mechanical attrition technique, the surface of a sample is deformed permanently. When the surface is bombarded with some high-speed steel balls, which gets energy from a high-frequency vibration generator (Figure 3).

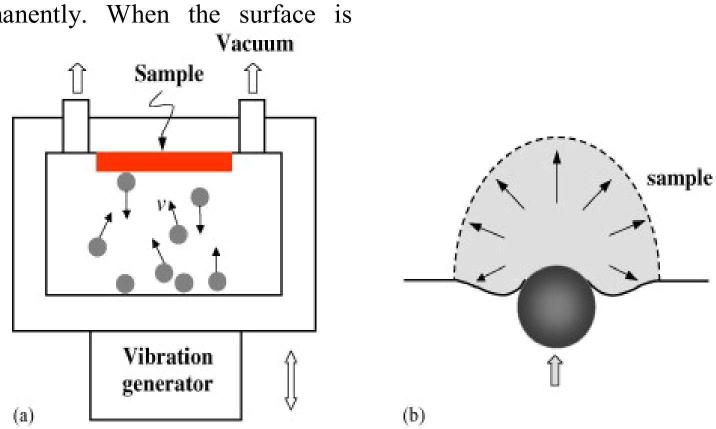

Figure 3. Schematic diagram of the surface mechanical attrition treatment set-up [39]

For advantages of this technique can be mentioned in improving the surface structure and some of the mechanical properties such as microhardness, grain size, and corrosion resistance of the treated sample. Figure 4 illustrates the effect of surface mechanical attrition treatment, where the ball hits the surface of the specimen. The peaks of the surface are rosined gradually, and the pits are filled. Also, eventually the roughness of the surface of the alloy is increased. Hu et al. showed that after treating NiTi SMAs by surface mechanical attrition, its surface hardness and wear resistance were increased [7]. Furthermore, Du et al. investigated that the corrosion resistance of NI-Fe SMA was improved after being treated by surface mechanical attrition [40]. The principle also works for shot-peening treatment, which is one of the mechanical treatment techniques.

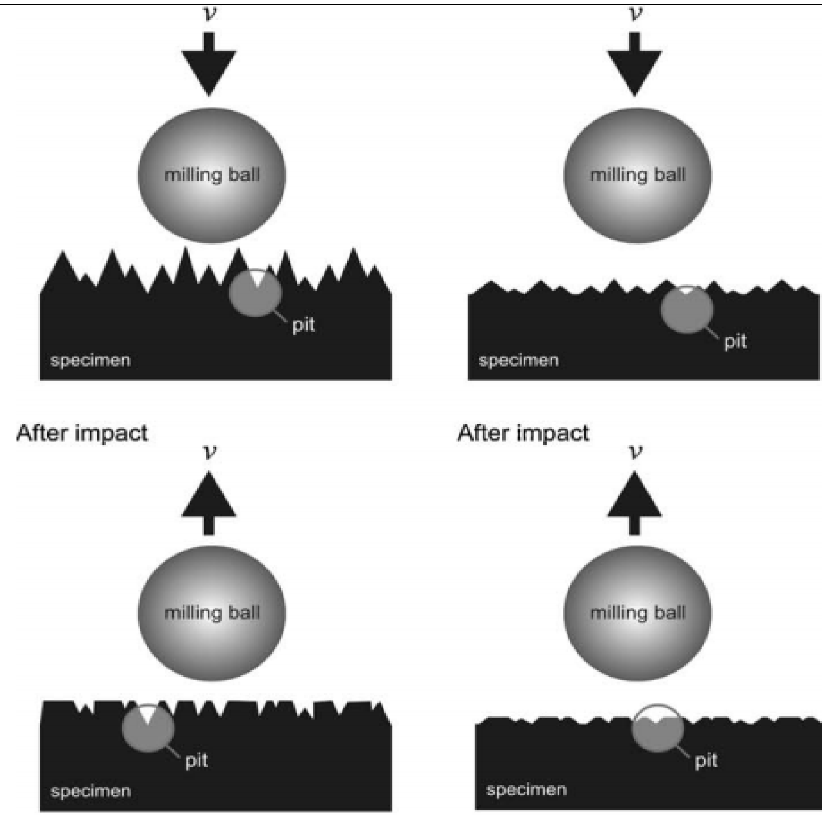

Figure 4. Effect of surface attrition treatment of roughness of the specimen surface [41]

3.1.3. Laser shock peening

Laser shock peening (LSP), is a surface treatment process that uses a high energy laser pulse. White in 1963 was the first person that used the laser pulse for the plastic deformation of metals [42]. Figure 5 demonstrates the experimental setup of the laser shock peening process. When the laser beams or pulse is hit the surface of metallic alloy in friction of the second (around 30 ns), the surface is heated, and its temperature increases to around 10000 ^{o}C. Also, the ionization process is performed on the heated portion of the surface to transform it into plasma, the plasma layer produces shock waves by the effect of laser energy. The plasma layer can interact with the surface by these shock waves, which improves the surface structure and some other properties of the alloy such as tensile strength, fatigue life, hardness, and resistance to cracking. Ye et al. performed the laser shock peening heat treatment process on NiTi shape memory alloy to investigate the effect of laser shock peening on the alloy. They found that the process could increase the hardness of the sample [43]. Also, Zhang et al. examined the same technique for NiTi SMA, where the hardness and corrosion resistance were increased, and the biocompatibility of NiTi alloy was enhanced [44].

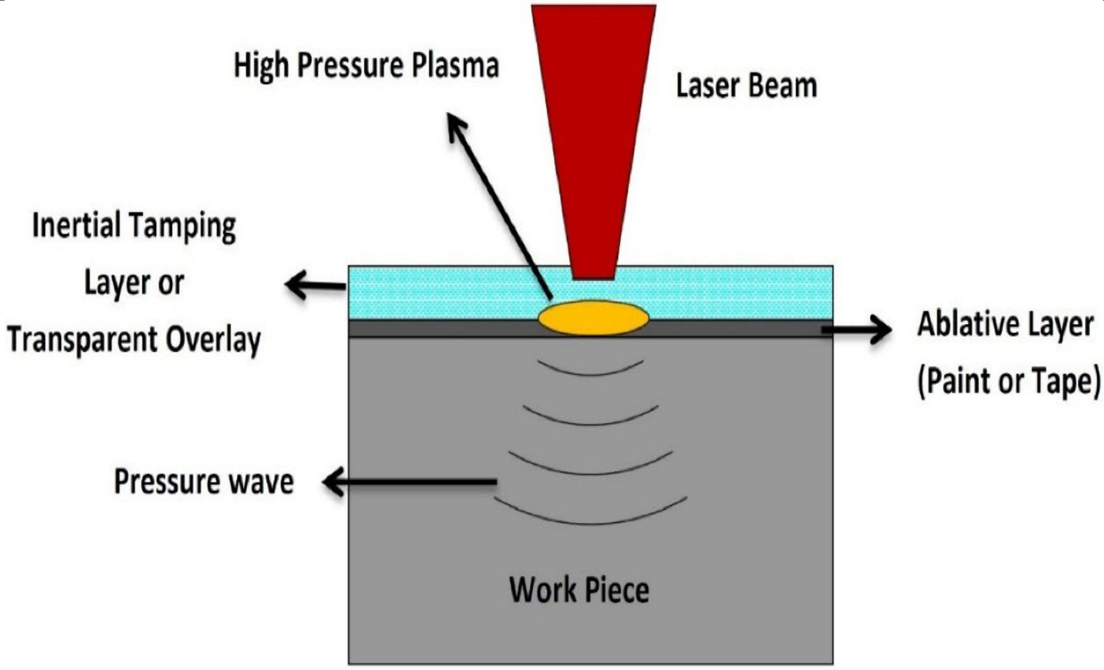

Figure 5. Schematic diagram of laser shot peening experimental set-up [45]

3.2. Thermal Treatment

Thermal treatment or heat treatment is a thermal process in material science that is used to treat or improve some physical and chemical properties of a material through heating or cooling the material to a certain temperature (Figure 6). Also, there are some other parameters such as cooling process, temperature, and time that can give a different characteristic to the material.

Heat treatment techniques have been widely used among metallurgists and it can be done by a furnace such as shown in Figure 6. The cooling processes can be accomplished in different mediums. Chu et al. examined this effect on the microstructure and physical properties of porous Ni-rich NiTi shape memory alloy. They found that the treatment could improve the ductility of NiTi SMA [10]. Balo and Sel studied the effect of thermal ageing on the physical parameters of CuAlNi SMA. They found that the Gibbs free energy and elastic energy of the treated sample increased about (%6-8) after 7 hours heat-treatment process. Also, the hardness of the treated sample was increased during the first two hours of ageing and then it decreased again to the same value as untreated samples [46]. Also, Sarı and Kırındı investigated that annealing heat treatment increased ductility and the strength of CuAlNi shape memory alloy [47]. The thermal treatment has several types but in technology and industry only four main types can be used, which are annealing, normalizing, hardening, and tempering.

Figure 6. An electrical furnace that is used to heat treatment of SMAs.

3.2.1. Annealing

The annealing process is a heat treatment process, in which the sample is heated in a furnace to a specific temperature (above critical temperature). And the sample is kept for some time at a specific temperature until recrystallization occurs on the sample (see Figure 7).

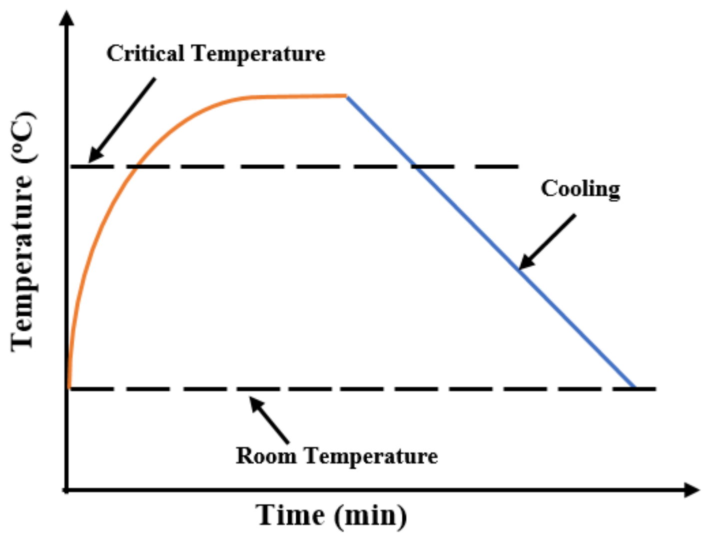

Figure 7. Schematic diagram of annealing treatment process.

Then the sample is cooled very slowly in the furnace (to growth equilibrium structure) to room temperature. Annealing treatment process increases some physical properties, which are dependence on heating and cooling rate. As an example, Wang et al. studied the effect of annealing treatment on shape memory recovery of NiTi SMA, where they found that the shape memory recovery of the alloy was increased by increasing the annealing temperature [11] (Figure 8).

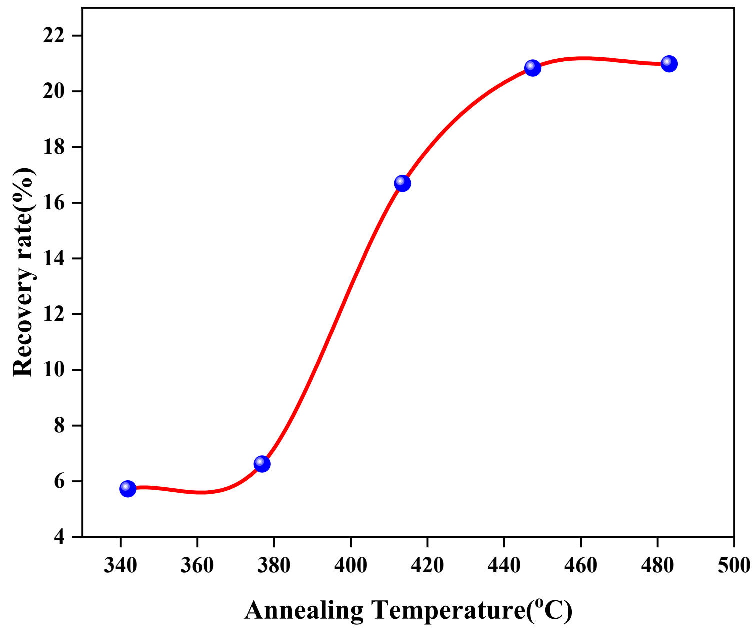

Figure 8. The shape memory effect of NiTi treated alloy vs. Annealing temperature [11]

Likewise, Yoon and Yeo reported the annealing treatment improved the phase transformation temperatures, thermomechanical behaviour, and crystal structure of NiTi SMA [48]. In addition, T Cheng was found that annealing treatment was significantly affected the ductility and toughness of NiAl SMA, [49]. Also, Zhuang et al. investigated in their work that the hardness of the alloy was reduced and the plasticity was increased [50] (see Figure 9).

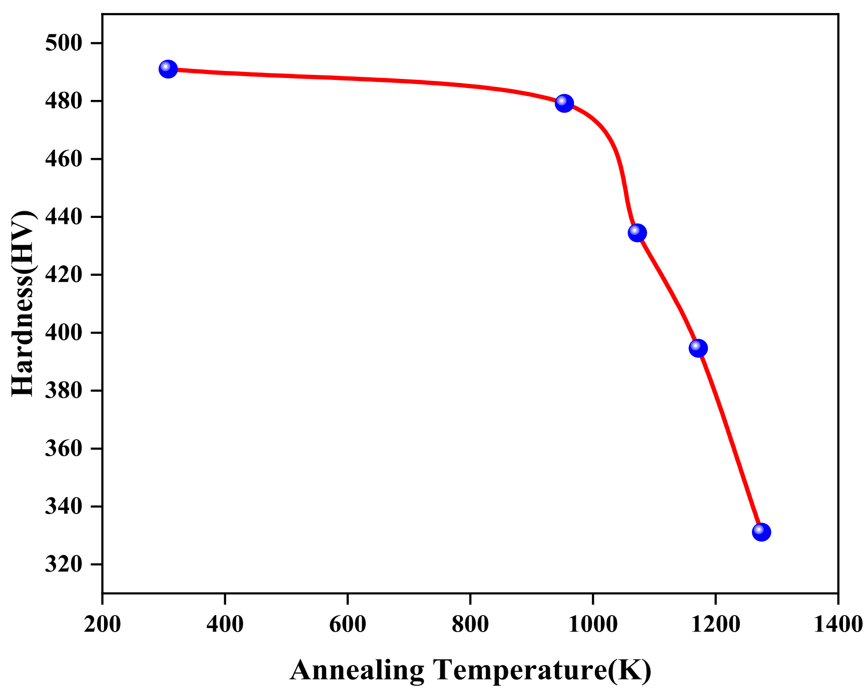

Figure 9. The hardness of (FeCoNiCuAl) is annealed at a different temperature [50]

3.2.2. Normalizing

Normalizing treatment is typically very similar to the annealing treatment process. It can be noticed that in both processes the sample was heated to a specific temperature (30-80 °C above recrystallizing temperature A_{C3}), kept for a period of time to reduce the brittleness and improve the ductility of the treated sample, and then cooled it down slowly in the air (Figure 10).

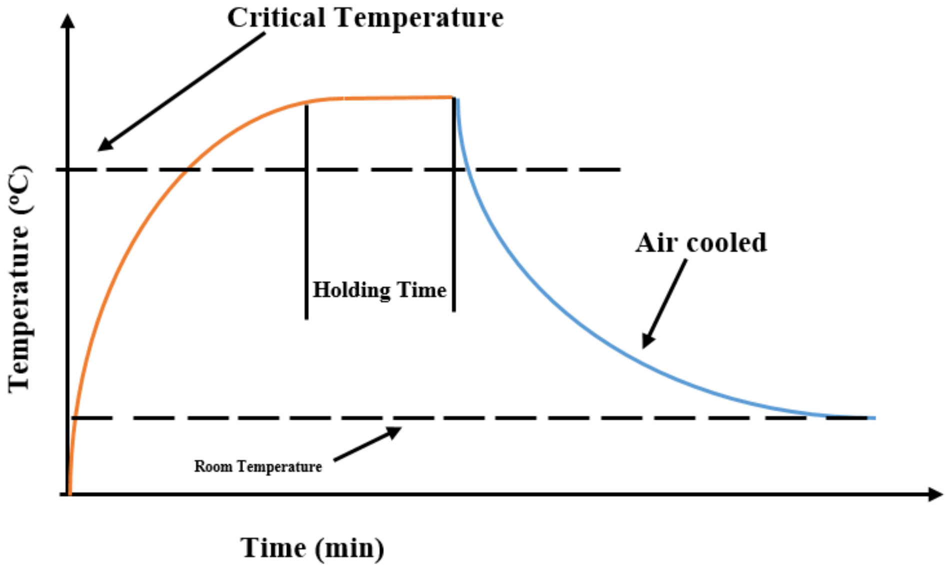

Figure 10 Schematic diagram of heating/cooling process of normalizing treatment.

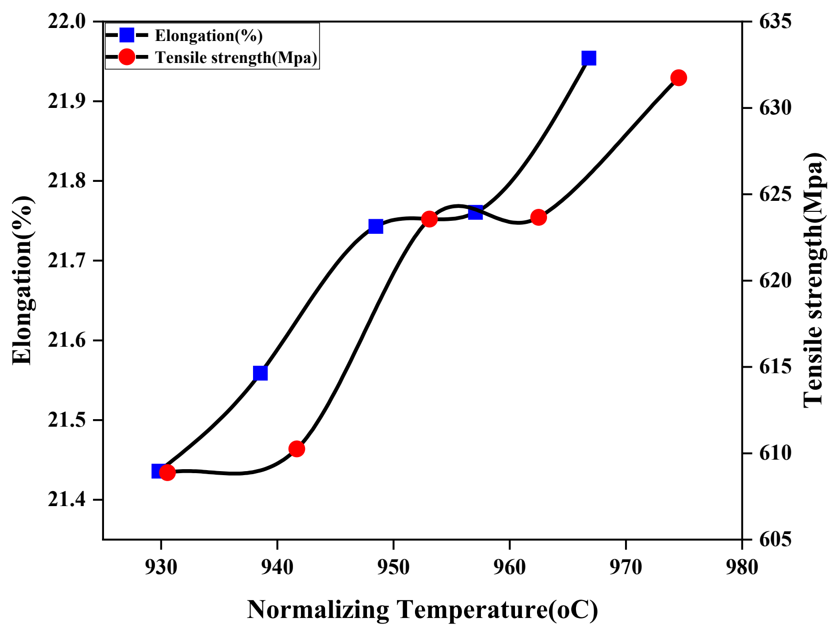

Figure 11. Effect of normalizing temperature on elongation and tensile strength of the heated sample [51]

However, the main difference between them is in the cooling process. in annealing treatment, the cooling process is performed in the furnace after heating, it needs more time for cooling because the environment inside the furnace is very hot, but in normalizing treatment, the cooling process is performing in the room environment, since the cooling process in the normalizing treatment is faster than in annealing treatment, so the normalized-sample is harder than the annealed-sample while normalized-sample has slightly less ductility than annealed one. Also, Sultan et al. realized that the normalizing process improved the tensile strength, failure stress, and yield strength of alloy [52], and Hu, et al. performed heat treatment on NiTi alloy by the normalizing process at a different temperature, they investigated that the normalizing treatment process was caused to improve the elongation rate and tensile strength of treated alloy (as shown in Figure 11) [51].

3.2.3. Hardening

Hardening as like all types of heat treatment processes while its temperature should not exceed critical temperature (Figure 12).

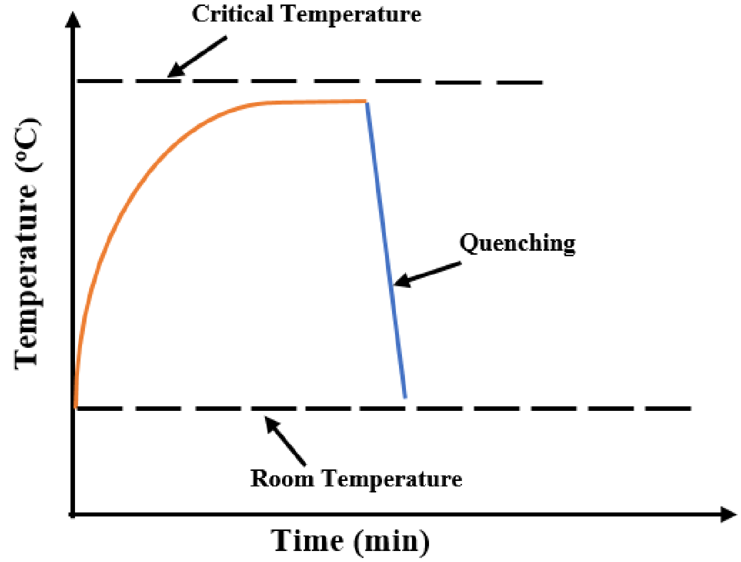

Figure 12. Schematic representation of hardening treatment process

It depends on the heating and cooling process, but hardening treatment is different from annealing and normalizing treatment in the cooling process. Because in hardening treatment after heating the sample in the furnace, it cooled rapidly (quenched) in oil, water, or saltwater. The hardening treatment can enhance the yield strength and hardness of the treated alloy (treated samples have more resistance to plastic deformation). Kamoshita et al. applied the hardening process to an Al-based SMA, where they found that the yield strength and hardness are improved compared to untreated samples [53].

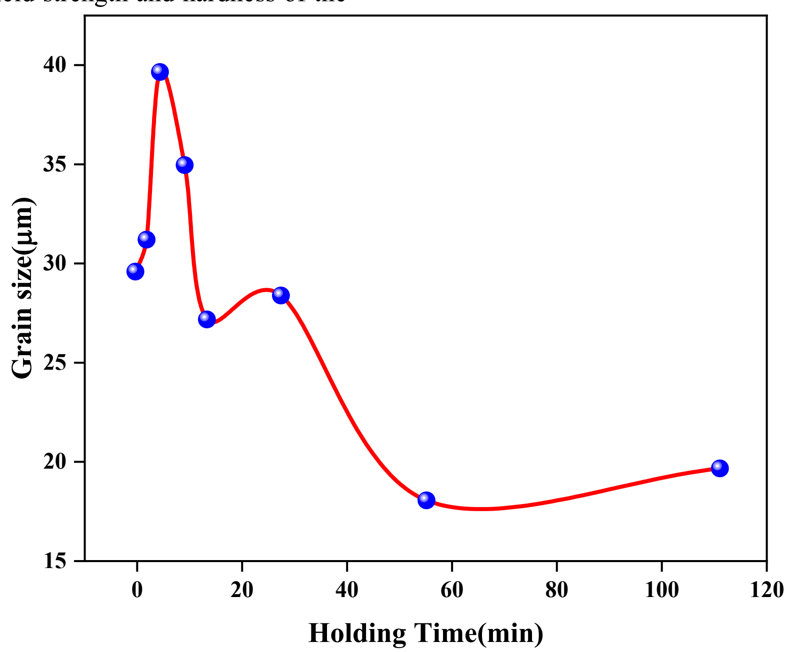

Figure 13. The relation between holding time and grain size in hardening treatment [54]

Nie et al. heated Mg–10Zn–6.8Gd–4Y to 580 °C alloy and isothermally held for 2.5, 5, 10, 15, 30, 60, and 120 min in the furnace, and then they cooled the alloy rapidly (quenched) in the saltwater, they saw that at the first 5 min the grain size of the treated alloy increased from ~30 µm to ~41 µm, but when the alloy held in the furnace for during more time, its grain size was decreased (Figure 13) [54].

3.2.4. Tempering

The tempering treatment process is another type of heat treatment process, which is used to give softness to the material. The tempering process is usually applied after the hardening process (Figure 14), when the treated sample is cooled in the hardening treatment process by quenching (cooling suddenly). To reduce its brittleness, the sample is heated again to a temperature below a recrystallizing temperature and then is cooled in the air. The tempering process has the effect to improve some of the physical properties of the treated alloy, in literature there are many practical works show the effect of tempering treatment. Mesquita et al. investigated that the tempering treatment caused to reduce the internal stress of the sample, decreased the hardness, and improved the roughness of the treated sample [55] (Figure 16).

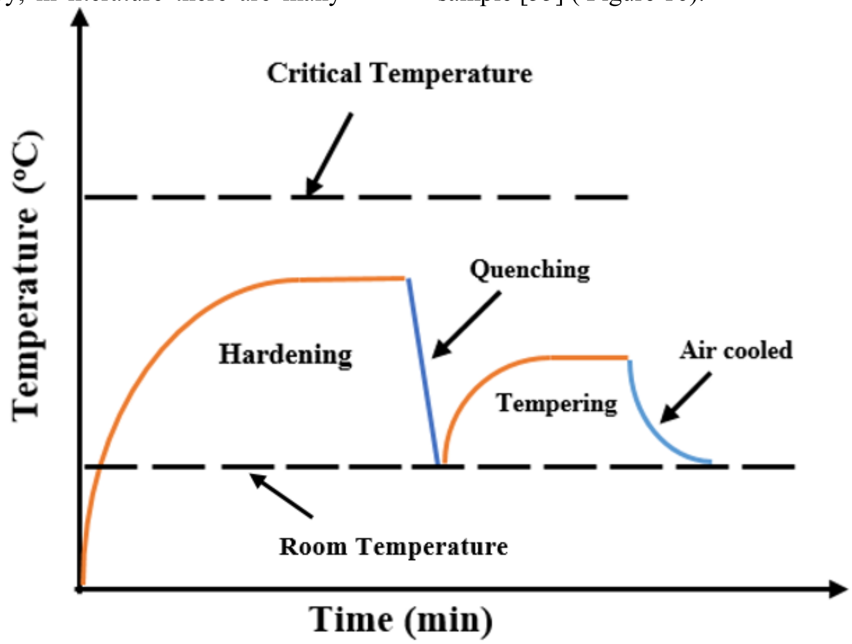

Figure 14. Schematic diagram of tempering treatment.

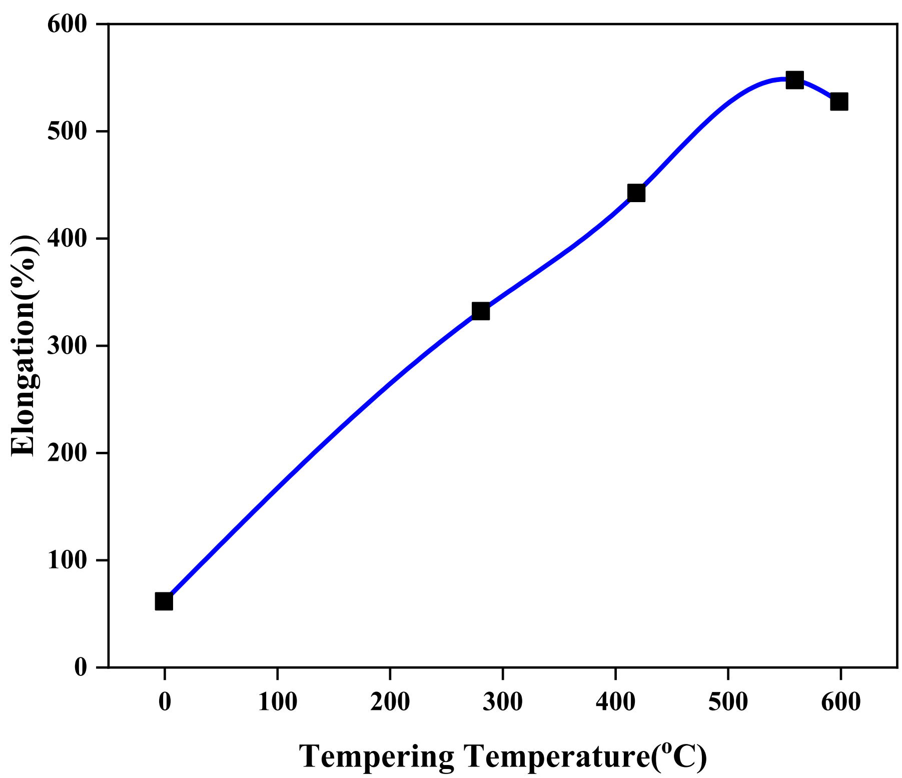

Figure 15. Relationship between Elongation and Tempering temperature [56]

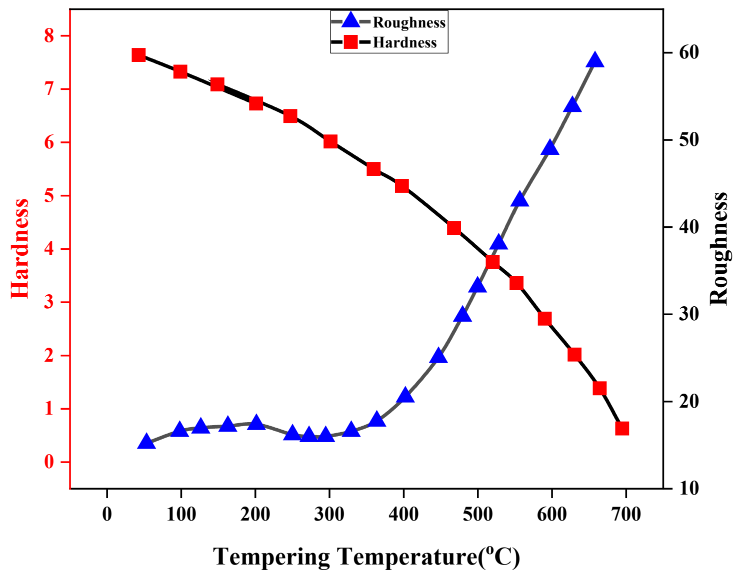

Figure 16. Tempering temperature vs. hardness and roughness of treated alloy [55]

Tabatabae et al. studied the effect of tempering treatment on ductility, elongation, and strength of an alloy sample, and they saw the tempering treatment is caused to improve the elongation rate (Figure 15) and reduced the strength of the heated sample (Figure 17) [56].

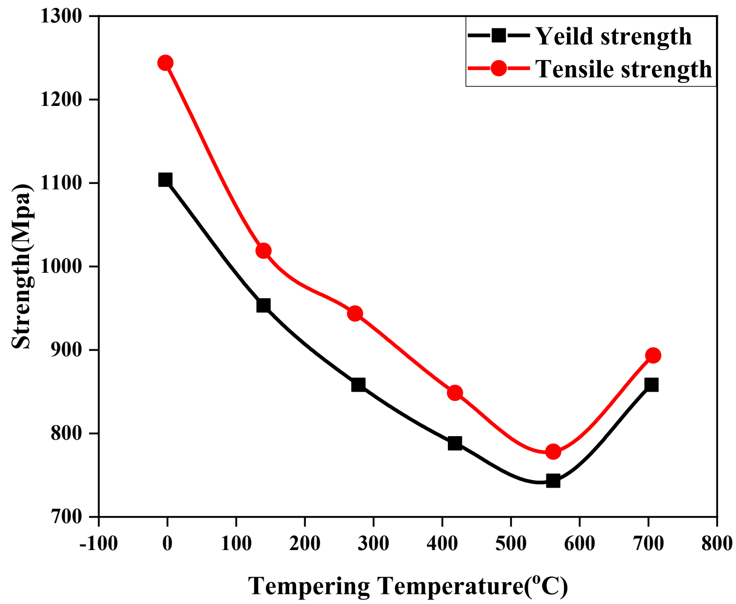

Figure 17. Effect of Tempering Temperature on tensile and yield strength of treated alloy [56]

4. Conclusion

In this study, both mechanical treatment techniques (Ball- and Roller-Burnishing Treatment, Surface mechanical attrition treatment, and Laser shock peening) and heat treatment techniques (Annealing, Normalizing, Hardening, and Tempering) have been clarified. And the effect of both treatment techniques on the properties of shape memory alloys has been reviewed.

After reading this review study we can conclude the following results:

Mechanical treatment.

1- burnishing mechanical treatment had a positive effect on surface hardness, wear resistance, and surface roughness of treated specimens

2- After treated SMAs by surface mechanical attrition, their surface hardness and wear resistance will be increased.

3- The laser shock peening treatment process will be caused to improve the hardness, corrosion resistance, and biocompatibility of NiTi alloy.

Heat treatment

1- The annealing treatment will improve the phase transformation temperatures, thermomechanical behaviour, and crystal structure of SMAs.
2- The normalizing process improved the tensile strength, failure stress, and yield strength of the alloy, also caused to improve in the elongation rate and tensile strength of the treated alloy.
3- The hardening treatment can enhance the yield strength and hardness of the treated alloy (treated samples have more resistance to plastic deformation).
4- The tempering process has the effect to improve some of the physical properties of the treated alloy.

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