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The Effect of Thermal Treatment Techniques on Physical Properties of Alloy and Composites: A Review

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ABSTRACT

Sometimes materials developed for use in technology have some shortcomings in that some of their properties need to be treated or further improved. There are several techniques to treat the shortcomings of materials, such as mechanical treatment, electrical treatment, surface treatment, chemical treatment, and heat treatment, each of these techniques has its characteristics, and each in some way attempts to fix the deficiencies of technological materials. This review focused on the heat treatment technique. There are four main types of heat treatment techniques: annealing, normalizing, hardening, and tempering. Each of them heats the materials and samples differently and cools them differently. Annealing, normalizing, hardening, and tempering have significant effects on improving the mechanical properties of materials including hardness, tensile strength, elongation, grain size, roughness and so on. This review attempts to analyze each of the four different heat treatment techniques, and the effect of each on the physical properties of solids is studied by reviewing the literature.

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1. Introduction

The development of any field of technology depends on the type and quality of the basic materials used. The better the capabilities and properties of the materials, the more successful the application. Alloy and composites play a major role in the development of technology [1-9]. However, sometimes some of the properties of the materials are weak and need to be improved. There are many scientific methods and techniques to treat and improve these properties such as mechanical treatment, electrical treatment, surface treatment, chemical treatment, and heat treatment [10-13], in heat treatment the material goes through an organized process of heating and cooling. This heating and cooling once again rearranges the lattice and atoms of the substance eliminating the weak qualities of the substance and improving its qualities. There are four main types of heat treatment (annealing, normalizing, hardening, and tempering), each of which has its own regulated heating and cooling process [14]. In the annealing procedure, the sample is heated in a furnace to a certain temperature (above critical temperature). The sample is then kept at a controlled temperature until recrystallization occurs. The sample is then progressively cooled in the furnace and generally it causes improved ductility and reduced hardness. In the normalizing process, the sample is heated in a furnace at a specific temperature (over the critical temperature), similar to the annealing process. The sample is maintained at a specific temperature for a period. But the cooling process is not carried out in the furnace but the sample is taken out and cooled in room air. The hardening treatment differs from annealing and normalizing in terms of the heating and cooling processes involved. During the hardening treatment, the samples are subjected to temperatures below the critical point in the furnace. Then they are rapidly cooled, or quenched, using oil, water, or saltwater. This process increases the hardness of the samples but may cause to decrease in brittleness. The tempering process is typically employed after the hardening treatment. In this process, the treated sample is cooled rapidly through quenching during the hardening treatment. To reduce brittleness, the sample is reheated to a temperature below the reconstructing temperature and subsequently cooled in air, tempering balances hardness and toughness by reheating the material to a lower temperature and then cooling it [11]. By controlling the heating and cooling rates, the microstructure of the material can be manipulated, leading to changes in grain size, dislocation density, and phase transformations. These alterations can

significantly impact the material's strength and toughness, making it more resistant to deformation and fracture. Furthermore, heat treatment can affect the electrical and thermal conductivity of alloys and composites. Heat treatment can be used to improve the electrical conductivity of copper or enhance the thermal conductivity of aluminium alloys [15].
This review attempts to analyze each of the four different heat treatment techniques, and the effect of each on the mechanical properties of solids is studied by doing literature research on the influence of various heat treatment treatments on the mechanical characteristics of various alloys and composites.

1. Heat Treatment

Heat treatment is one of the most important and useful techniques in materials engineering. It is used to change the qualities of metals so that they work better in certain situations. In this process, heat is carefully applied to an object, and then it cools down in a controlled way. The main goal of heat treatment is to change the material's substructure, which changes its physical, chemical, and sometimes mechanical qualities. One popular way is annealing, which means heating the sample to a specific temperature and then slowly letting it cool down. Annealing lowers internal pressures, makes the material more flexible, and smooths out the grain structure, all of which make it easier to work with [11].
Another important heat treatment method is quenching, which involves quickly cooling the material, usually in water, oil, or air, to get the stiffness you want. Because of this process, a rigid particle like martensite forms in the metal. However, the extreme cooling can cause internal pressures that need to be tempered later. To temper something, you heat it again to a lower temperature. This lets you change how hard it is. This fine balance is very important because it gives the material power while keeping its flexibility [16].
A lot of steel is made with heat treatment. During processes like austenitizing, melting, and tempering, the exact rates of heating and cooling can be controlled to get certain microstructures and mechanical qualities. For example, high-carbon steels can be strengthened to make cutting tools that last, and low-carbon steels can be softened to make parts that are tough and won't break when hit [17].
In addition to steel, heat treatment is used in many other fields, such as aircraft, automobiles, and industry. Because heat treatment can change the qualities of materials, engineers can get the best performance from things like hardness, strength, and resistance to wear [17-20]. Even though materials science and engineering are always changing, heat treatment is still an important way to get the right mix of qualities in metals.
Metallurgists use heat treatment methods all the time, and a furnace like the one in **Figure 1** can be used to do it. Different mediums can be used for the cooling process. In their study, Cheng-lin CHU et al. investigated how heat treatment affected the physical characteristics and microstructure of a shape memory alloy that included porous Ni and Ti. These researchers discovered the ductility of NiTi SMA enhanced by heat treatment. [21]. The impact of thermal ageing on the physical characteristics of CuAlNi SMA has been studied by ŞN Balo, N Sel. After subjecting the sample to heat for 7 hours, they discovered that its elastic energy and Gibbs free energy rose by around 6 to 8 per cent. In addition, the treated samples' hardness grew during the first two hours of ageing [22]. Additionally, research carried out with U Sarı and T Kırındı in 2008 found that the ductility and strength of CuAlNi shape memory alloy were enhanced with annealing heat treatment. [23]. Tempering, annealing, normalizing, and hardening are the four most common forms of thermal treatment in technology and industry, however, there are many more.

Figure 1. Electrical furnace.

1.1. Annealing

Annealing is an important heat treatment method used in materials engineering to change the composition of metals and improve their qualities. To do this, the material is heated to a certain temperature and then slowly cooled down (**Figure 2**), usually in a controlled space like a furnace [11, 24]. The main purpose of annealing is to reduce stresses inside the material, cause recrystallization, and encourage grain growth. Because of this, the metal's mechanical features get better, making it more flexible and less hard. When steel and other metals are being made, annealing is very helpful because it can smooth out the crystal structure of the material, making it easier to shape and work with in later steps. Some types of annealing processes are stress-releasing and full annealing. During the process of full annealing, the material is subjected to heating beyond its critical range. And then slowly cooled [25]. Stress relieving aims to lower the internal pressures in the material without changing its microstructure significantly. Many different fields, from metals to electronics, use annealing [26-28]. It is a flexible way to change the mechanical features of materials for different uses. An important job of annealing is to find the best balance between strength and flexibility. This makes it one of the most important heat treatment methods [29].
Zhiguo Wang and colleagues carried out a study to investigate the significance of annealing treatment on the

form memory recovery of NiTi shape memory alloy material. They discovered that the annealing temperature had a significant impact on enhancing the shape memory recovery of the alloy. [30] **(Figure 3)**.

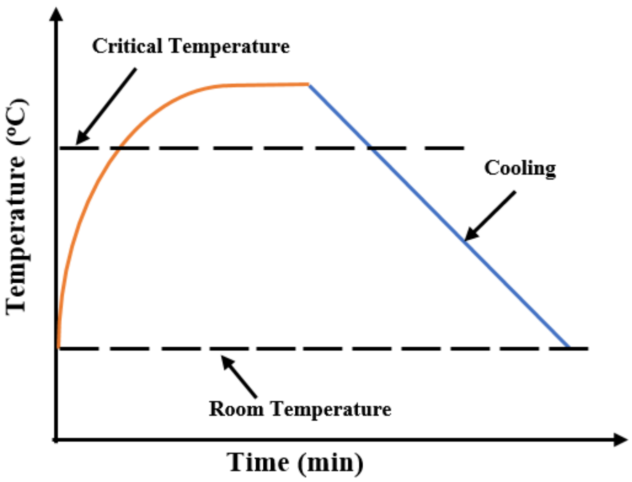

Figure 2. Procedure of annealing treatment process.

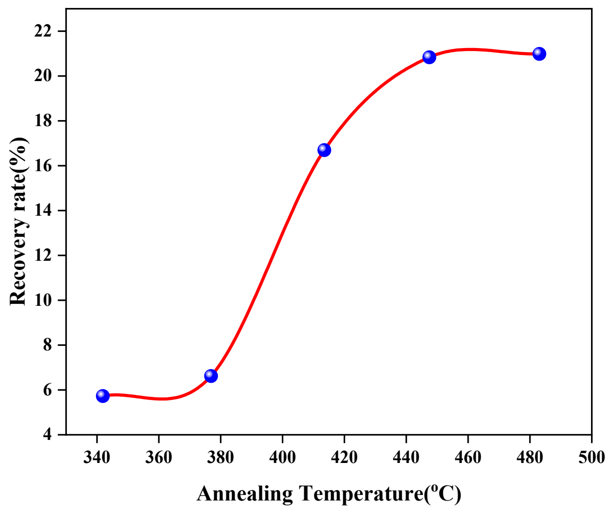

Figure 3. The shape recovery vs. Annealing temperature to NiTi-treated alloy [30]

Similarly, the annealing process caused to enhance the phase transition temperatures, thermo-mechanical properties, and crystal arrangement of NiTi SMA, as reported by Yoon, S.H., and Yeo, D.J [31]. Moreover, T Cheng investigated the effects of annealing on the ductility and toughness of NiAl alloy, and he observed that it had a substantial impact on both properties [32]. Additionally, Y.X. Zhuang et al. discovered in their research that the plasticity of Fe Co Ni Cu Al alloy was enhanced while its hardness decreased. [33] (see **Figure 4**).

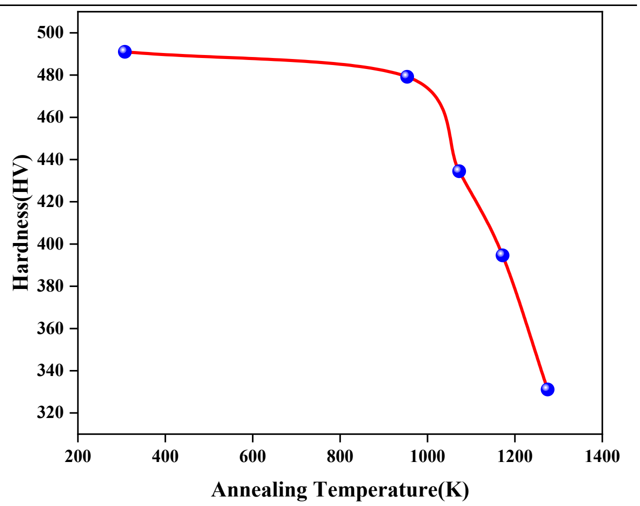

Figure 4. The hardness of (Fe Co Ni Cu Al) alloy that annealed at different temperatures [33].

Khumo Masemola and co-workers annealed the arc-melted Al-Cr-Fe-Mn-Ni equi-atomic High entropy alloy at 200, 400, 600, 800, and 1000 °C [34]. They examined the effect of the annealing process on the hardness of the high entropy alloy as shown in **Figure 5** the annealing at low temperatures (200 and 400 °C) caused to increase in the hardness of the alloy and they showed that the hardness of the samples decrease by increasing the annealing temperature. Also, they investigated that the wear rate of the sample enhanced after annealing treatment.

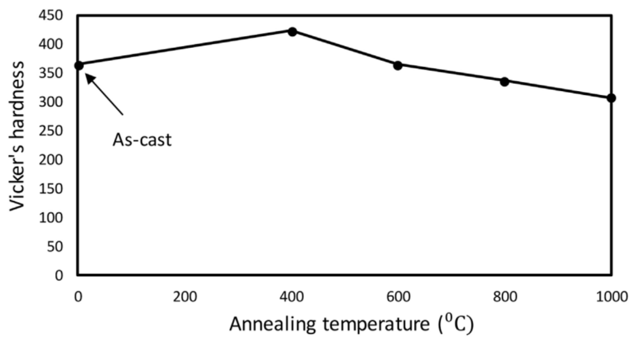

Figure 5. effect of annealing treatment on hardness on Al-Cr-Fe-Mn-Ni High entropy alloy[34].

O.O. Salman, et al. examined that the annealing treatment increased the cell size of 316L steel synthesized by selective laser melting when they saw after annealing the sample at 573 K and 873 K, the cell size increased from 520 ± 10 nm for the as-casted sample to 773 ± 7 and 938 ± 6 nm. Also, they examined that the size of grains was increased by increasing the annealing treatment temperature (as shown in **Figure 6**). However, the strength of 316L steel samples was decreased after increasing the annealing temperature (**Figure 7**) [35]. Annealing treatment has been applied to alloys and composited by many other researchers in the literature [33, 36-40].

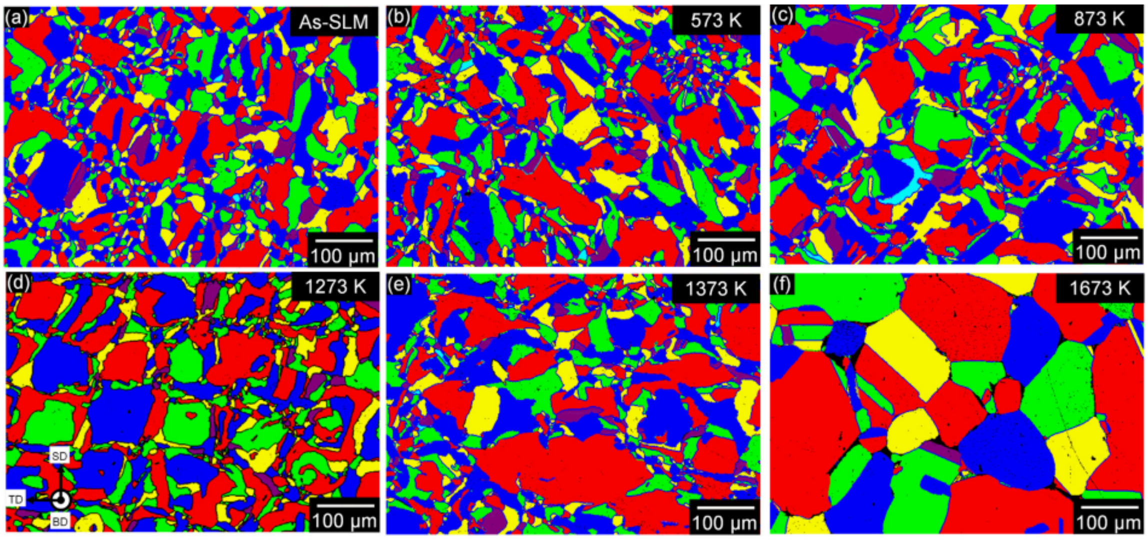

Figure 6. SEM images of (a) as-casted 316L steel sample and annealed samples at (b) 573 K, (c) 873 K, (d) 1273 K, (e) 1373 K and (f) 1673 K [35].

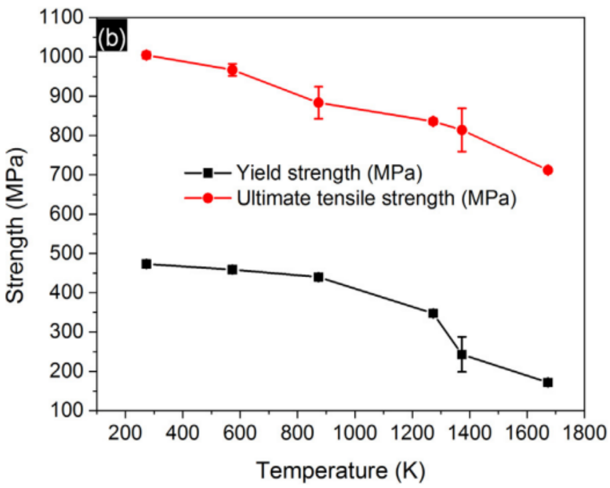

Figure 7. represents the effect of annealing treatment on the strength of 316L steel[35].

1.2.Normalizing

Normalizing treatment is a type of heat treatment, to improve the composition of metals, especially steels. Heating the material above its critical temperature and letting it cool in still air helps make the grain structure more regular[41]. Regularizing gets rid of internal pressures and improves mechanical qualities like toughness and durability. Especially, it offers these benefits without the risk of warping or breaking, which makes it a popular choice in fields like manufacturing and building where exact control over material integrity is important. Normalizing helps make high-quality materials that work regularly in many situations [11, 19].

Normalizing treatment is similar to annealing treatment in which the sample is heated in a furnace between 30 and 80°C, and kept at that temperature for a while to remove brittleness and improve ductility, then removed from the furnace and then slowly cooled in air (**Figure 8**). Nevertheless, the primary distinction is in the cooling procedure. In the annealing treatment, the cooling process takes place in the furnace after heating. Due to the high temperature inside the furnace, it requires more time for the cooling process. On the other hand, in the normalizing treatment, the cooling process takes place at room temperature [11, 41]. The cooling process in the normalizing treatment is more quickly than in the annealing treatment. As a result, the normalized sample is harder than the annealed sample, although it has slightly less ductility compared to the annealed sample [42]. Additionally, Sultan et al. observed that the alloy's yield strength, tensile strength, and failure stress were all enhanced by the normalizing method. [43],

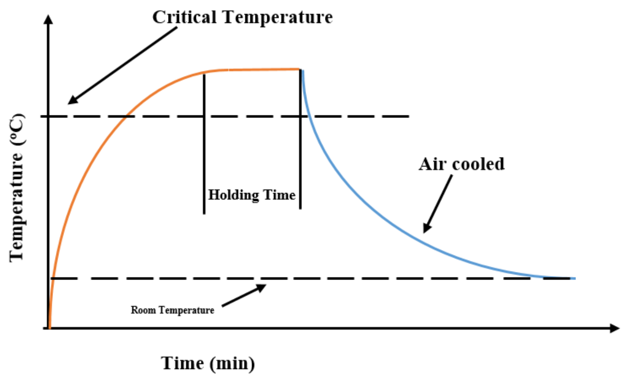

Figure 8. Normalizing Treatment Performance Diagram.

ZJ Hu et al. subjected NiTi alloy to a normalizing treatment at a temperature difference; they determined that the alloy's tensile strength and elongation rate were increased by normalizing treatment (as shown in **Figure 9**) [44].

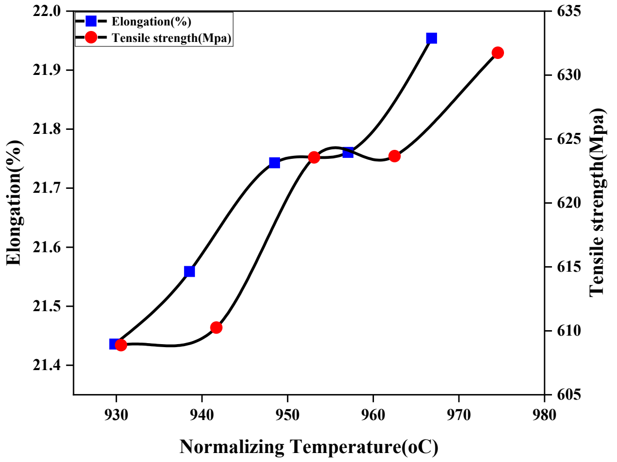

Figure 9. Enhancing the elongation and tensile strength of NiTi alloy by normalizing temperature [44].

Dipika R. Barbadikar and co-workers applied the normalizing and tempering treatment on P92 steel at three different temperatures (1313 K, 1335 K, and 1353 K) [45], they studied that the hardness, grain size, yield strength, and tensile strength are affected by normalizing treatment. They examined that the normalizing treatment caused to increase in the grain size of P92 steel (**Table 1**), but the hardness of the sample was decreased after the normalizing process this is because of grain size enhancement (the relationship between hardness and grain size is inversely proportionality [46]). Also, they investigated that both tensile strength and yield strength were increased by increasing the normalizing temperature.

Table 1. Changing of hardness and grain size of P92 steel after normalizing treatment [45].

Normalizing temperature (K)	Grain size (μm)	Hardness (Hv)
1313	28	421
1335	37	401
1353	55	390

GJ Sun, et al. [47]tested the effect of normalizing and cast treatments on the mechanical behaviors of TiCp/Fe composites, they saw that wear resistance, hardness, and impact toughness of the samples were improved by normalizing treatment. Also, M Gupta and colleagues showed that the grain size of both Al-Li and Al-Li-Sic composites increased after increasing both the normalizing temperature and the normalizing time [48] (**Figure 10**). ‘ These are some examples of heat treatments by normalizing for alloys and composites [49-55].

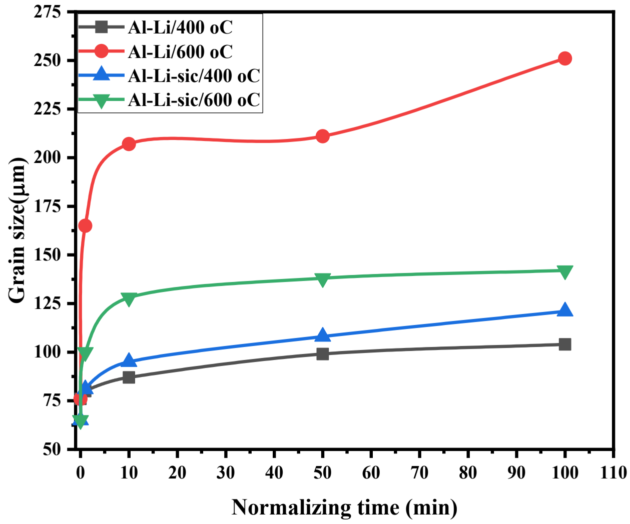

Figure 10. effect of normalizing temperature and normalizing time on the grain size of Al-Li and Al-Li-Sic composites [48].

1.3. Hardening

In metallurgy, hardening treatment is an important heat treatment method used to make metals, especially steels, stronger and harder[56]. The main goal of hardening is to change the architecture of a material by heating it to a certain temperature and then quickly cooling it, usually by soaking it in water, oil, or some other liquid [19]. Because it cools so quickly, bigger crystals can't form, which makes the structure harder and more fragile. The process of strengthening greatly enhances the material's mechanical qualities, such as its resistance to wear and toughness, making it perfect for tough uses [11]. While making something harder is usually a good thing, it often means that it is less flexible. So, tempering, which is the next step in the heat treatment process, is often used to make the metal less brittle and find a good balance between hardness and stiffness [57]. For cutting tools, gears, bearings, and other parts that are subject to a lot of stress and wear, hardening is a common process [58]. Hardening treatment gives exact control over hardness and strength, which is important for making materials that can work in tough situations in fields like aircraft, automobile, and tool manufacturing [59].
During the hardening heat treatment operations, it is important to ensure that the heating temperature is not above the critical temperature (**Figure 11**).

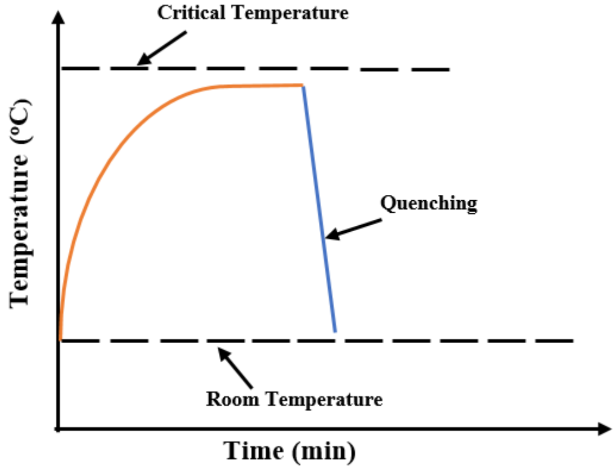

Figure 11. Hardening treatment process diagram.

The difference between hardening treatment and other treatment processes is in the cooling process because in the hardening treatment, the treated sample quickly cooled (quenched) in oil, water, or salt water [60]. The process of hardening treatment may significantly improve the yield strength and hardness of the alloy being treated, resulting in increased resistance to plastic deformation in the treated sample [11]. Based on their application of the hardening procedure to an Al-based SMA, Kamoshita et al. discovered that the yield strength and hardness of the material were significantly increased in comparison to samples that had not been treated. [61].

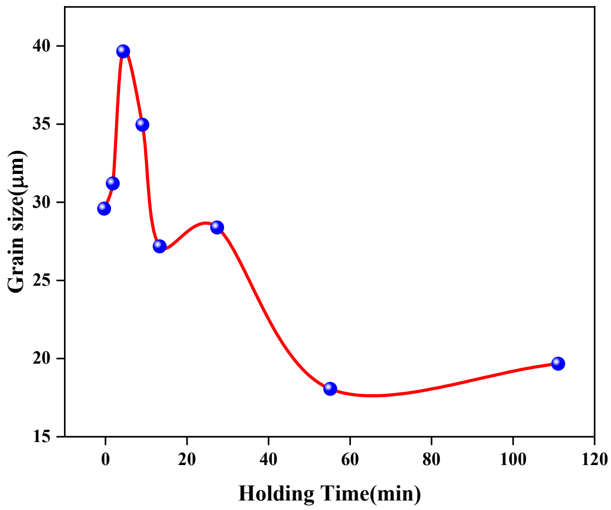

Figure 12. Effect of hardening treatment holding time on grain size in Mg-(10)Zn-(6.8)Gd-(4)Y [62].

Shuang Nie et al. hardened Mg-(10)Zn-(6.8)Gd-(4)Y in the degree of 580 ◦C for (2.5, 5, 10, 15, 30, 60, and 120 min). They investigated that after cooling the treated alloy quickly (quenched) in the saltwater firstly in 2.5, and 5 minutes the grain size of quenched sample increased, but when the holding time increased (for 10, 15, 30, 60, and 120) the hardening treatment has the negative effect on the alloy because the grain size of the alloy was decreased (**Figure 12**) [62]. It was shown by Min Shan HTUN and his colleagues that the hardening resulted in a decrease in the hardness of spring steel. Furthermore, they saw the same effect when the holding time of the treated sample was increased (**Figure 13**) [63].

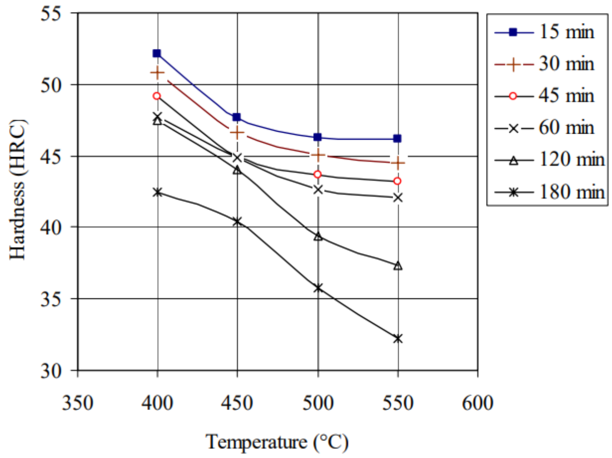

Figure 13. effect of hardening treatment on the hardness of spring steel [63].

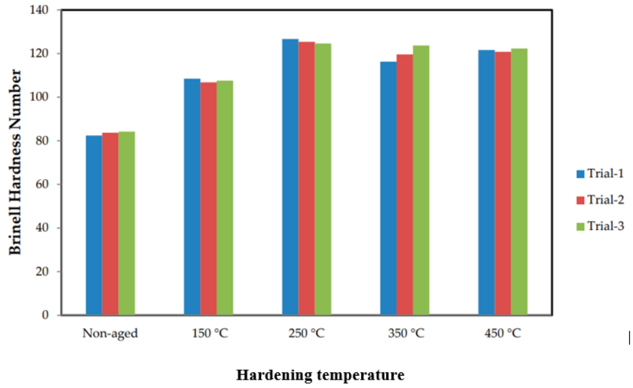

Figure 14. the effect of hardening treatment temperature on the hardness of Al7075-Tungsten Carbide Composite [64].

The effect of hardening treatments on the properties of composites depends on several factors, including the type of composite material, the reinforcement used, and the specific hardening method employed. Generally, hardening treatments are designed to enhance the mechanical properties of composite materials.

The work of S Rajaram and colleagues showed that the hardness of the Al7075-Tungsten Carbide Composite was enhanced after increasing the hardening temperature, and they noticed that the hardened sample at 250℃ has the maximum value (**Figure 14**). Also, as shown in **Figure 15** they investigated that the hardening temperature increased the tensile strength of Al7075-Tungsten Carbide Composite, but the increase is not linearly and as hardness, the tensile strength has the maximum value at 250℃ of temperature [64]. Also, many other works investigated the effect of hardening treatment on the physical properties of Alloys and Composites [65-71].

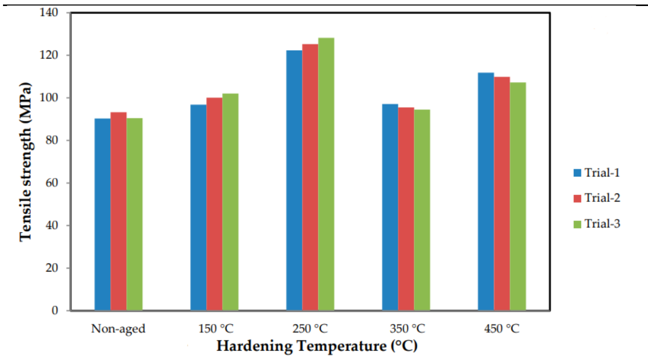

Figure 15. Relation between hardening temperature and tensile strength of Al7075-Tungsten Carbide Composite [64].

1.4.Tempering

Another type of heat treatment that is used to make something soft is the tempering treatment. Usually, it is done after applying the hardening process (**Figure 16**), when the sample is quenched to quickly cool it down during the hardening treatment. The sample is heated again to a temperature range less than the recrystallizing temperature and then left to cool in the air. This makes it less brittle [11, 72].
Some physical properties of treated samples will improve after treatment by tempering treatment, it decreases the excessive hardness that is obtained during the hardening process, hence improving the toughness, ductility, and impact resistance [73, 74]. Tempering is a crucial process used in the manufacturing of tools, springs, and structural components. Its main purpose is to provide a harmonious blend of strength and resilience in materials [75]. This is important for assuring maximum performance in applications where both of these properties are necessary for longevity and dependability. There are many practical works showing the effect of tempering treatment in the literature. According to research by R.A. Mesquita et al., the tempering process lowered the sample's internal stress, which made it less hard, and increased its roughness. [76]. **(Figure 17**).

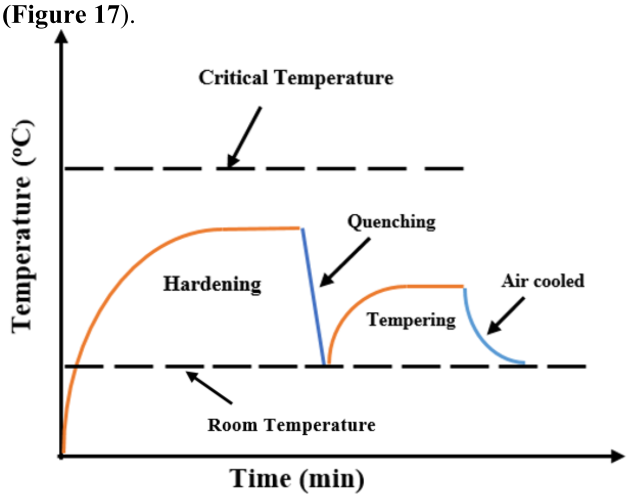

Figure 16. Tempering treatment.

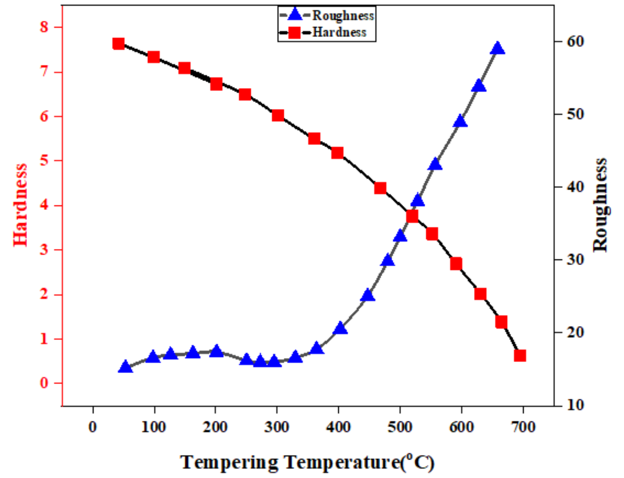

Figure 17. Effect of Tempering temperature on hardness and roughness of treated sample [76].

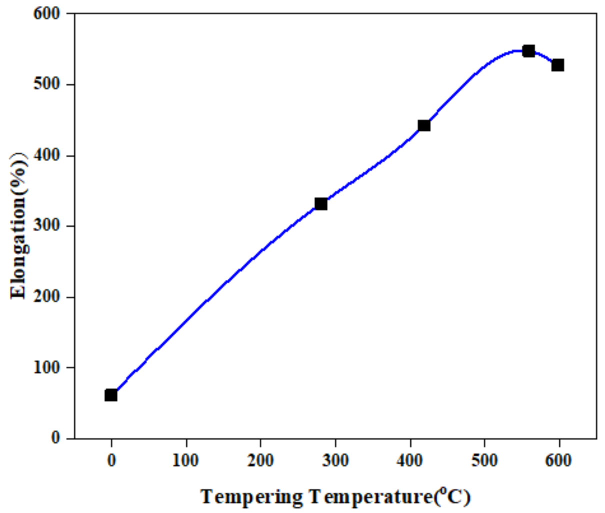

Figure 18. Change of Elongation by tempering treatment [77].

Also, BA A study was conducted by Tabatabae and colleagues to investigate the effect of the tempering process on the ductility, elongation, and strength of an alloy. The researchers discovered that the tempering treatment led to an increase in the elongation ratio (**Figure 18**), while simultaneously reducing the strength of the sample. (**Figure 19**) [77].

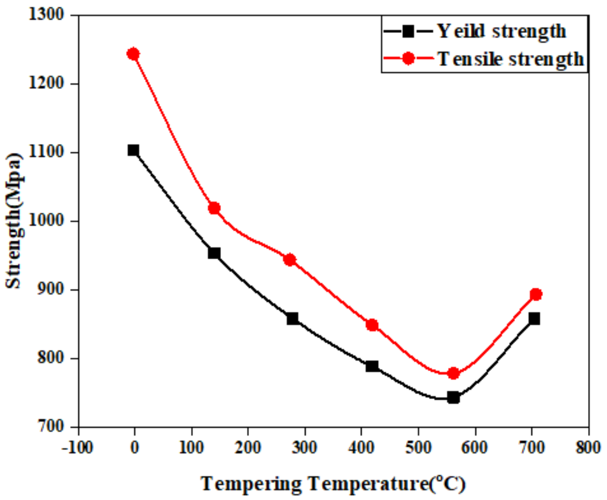

Figure 19. the relation between Tempering temperature with tensile and yield strength of heat treated sample [77].

In the study of Yu Li and co-workers for increasing strength, toughness, and plasticity, the ultra-low carbon medium-Mn steels were subjected to the tempering treatment following an inventive quenching-partitioning-tempering (QPT) procedure with various starting conditions, 17 cold rolling (CR) and hot rolling (HR). They held the samples for about 1 hour at 500℃, and they investigated that the yield strength, tensile strength, elongation, and hardness of ultra-low carbon medium-Mn steel samples were increased after tempered (**Table 2**) [78]. Also, there are many works in the literature about tempering heat treatment [75, 79-83].

Table 2. Change of properties of ultra-low carbon medium-Mn steels by tempering treatment [78].

Treatment	Yield Strength (Mpa)	Ultimate Tensile Strength (Mpa)	Total Elongation (%)	Vickers Hardness (Hv)
Temperature	RT	RT	RT	RT
CR-QP	647+15	928+23	20.3+1.7	187+5
CR-QPT	971+20	984+13	27.9+1.5	359+4
HR-QPT	902+15	988+16	24.8+0.8	365+5

Conclusion

In conclusion, this comprehensive review examines thermal treatment techniques and their significant impact on the mechanical and physical properties of alloys and composites. Heat treatment processes, such as annealing, normalizing, hardening, and tempering, are essential in customizing the properties of materials to fulfil specific technological needs. The process of annealing, characterized by precise heating and gradual cooling, plays a significant role in enhancing flexibility, reducing hardness, and improving mechanical properties, thereby effectively addressing material limitations. The process of normalizing, which is similar to annealing, is employed to improve the grain structure and enhance mechanical properties, specifically the tensile strength. The hardening treatment, known for its unique rapid cooling process, enhances hardness and strength, making it well-suited for applications that demand durability and resilience against wear and stress. Nevertheless, the fragility that arises during the hardening process requires the implementation of tempering, which is a subsequent procedure aimed at reinstating flexibility and achieving a harmonious equilibrium between hardness and toughness. Every treatment method has an impact on various parameters, including hardness, tensile strength, ductility, grain size, and roughness. These parameters are of utmost importance in a wide range of applications across different industries.

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