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# A Review of Positive Effects of Metal Hardening Process in Heat Treatment

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**Abstract—** In metallurgy, hardening is a process used to improve the hardness of a metal. In today's era, there are many different types of metal hardening processes known to be employed in order to make certain metals better suited to their purposes. Mechanical properties of metals can often be enhanced using heat treatment. In heat treatment, metals or alloys are heated to specific, often very high, temperatures and then cooled in order to harden the material.

**Keywords >>** Discuss on a metal hardening, heat treatment, annealing, precipitation hardening, strength.

## 1 Introduction

## Metal Hardening Processes

The most common type of metal hardening process is martensitic transformation, which is usually performed on steel. In this method, steel is heated to very high temperatures and then quenched. This allows the crystal structure inside the steel to remain in a certain state, which makes steel hardened and better suited to withstanding large amounts of wear and tear. During the hardening process, steel goes through a number of different states and it may be desired to quench it at any point during the process, depending upon the certain type of steel hardness required.

There are other common types of metal hardening processes include annealing, case hardening and precipitation hardening. Each of these processes serve to harden a metal in order to improve properties such as strength, durability, ductility and toughness. Vasiliev et al. (2003) sought to perform modelling of the metal hardening process, whereby the two main hardening methods employed were impact induction heating followed by cooling, and impact induction heating without cooling (quenching). The authors suggested that employing induction heating without quenching could be beneficial in certain cases. Figure "1" demonstrates a representation of the data obtained for the hardening process.


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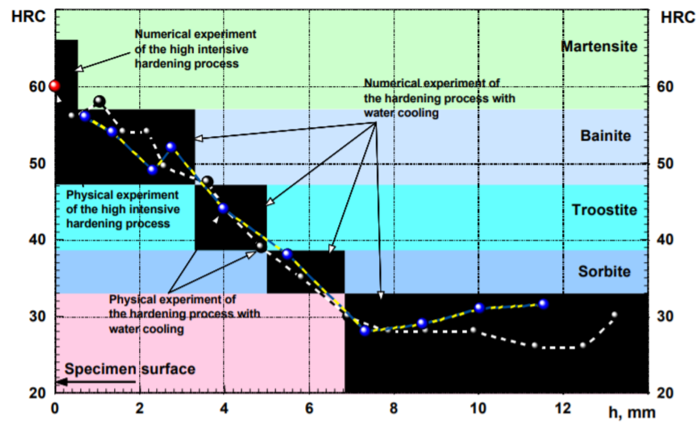

Figure 1: Hardening process data (Vasiliev et al., 2003)

In their modelling approach, the authors used a mathematical model based on a 2D electromagnetic phenomenon as well as the non-linear Fourier transformation. For the hardening process, the maximum upper bound for temperature was determined to be 1200℃, and a structure change diagram was also developed using an algorithm-based approach.
Through a series of physical experiments and process modelling, the authors determined domains for the hardening process and determined high intensity heating by induction was a viable method to improve hardness of metals without employing quenching, as shown in figure 1 (Vasiliev et al., 2003).

In a similar vein, Ge et al. (2006) considered various parameters for the induction hardening process. The authors recognized the usefulness of induction hardening for improving hardness of electrically conductive metals. They suggested this to be a complex process involving electromagnetic, heat transfer and metallurgy-related factors. In order to assist the design of induction hardening devices, the authors performed detailed modelling including a consideration of the dynamic behaviour of load impedance. Results from the study suggested that induction hardening could lead to formation of desirable steel phases such as martensite while avoiding melting of the surface (Ge et al., 2006).

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The effects of precipitation hardening heat treatment are often desired to be explored, particularly on the structural and performance parameters of a metal. Pabandi et al. (2018) sought to study this, and the metals under consideration were specific types of aluminium alloy sheets. Specifically, the authors sought to understand effects of friction stir welding on the samples in retreating and advancing sides. Scanning Electron Microscopy (SEM) was used to analyse the macro and micro-structures of the welded joints along with micro-hardness and tensile tests performed to determine the mechanical properties of the joints (Pabandi et al., 2018).

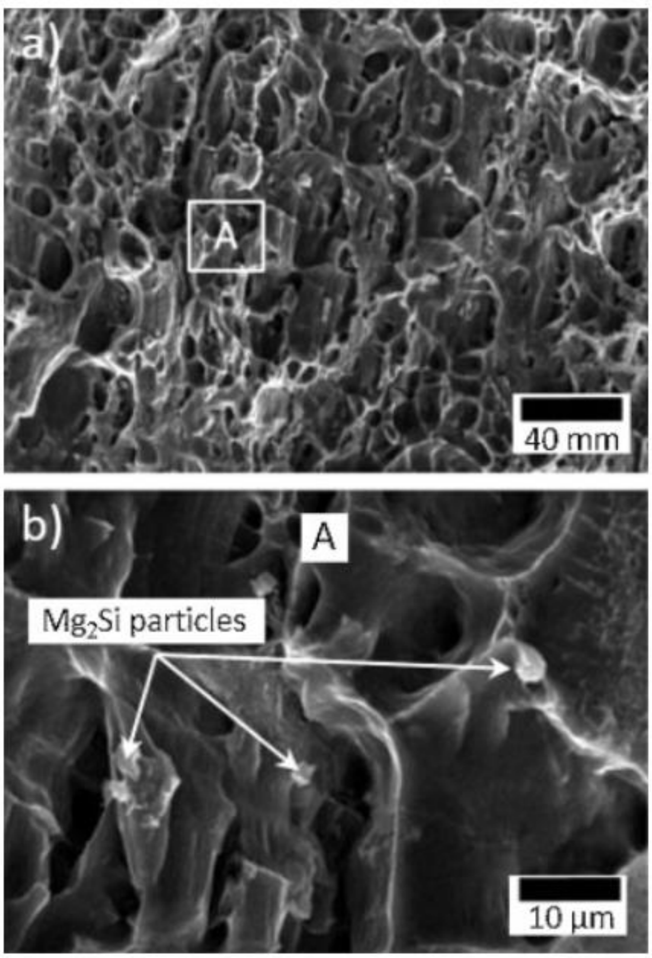


Figure 2: SEM analysis showing (a) top view of the fracture and (b) precipitated Mg2Si particles (Pabandi et al., 2018)

Findings from the study demonstrated that, following precipitation hardening, the microstructure of the welded joints was made up of coarse grains which extended all the way into the base metals for the welded zones. The grains also grew larger in size. The ultimate tensile strength of the heat-treated parts was higher as compared to the non-heat-treated parts of the welded joints. This demonstrates the increase in strength and hardness of the sheets depending upon heat treatment. SEM studies showed certain nucleation sites on the fracture surface, as shown in figure 2 above (Pabandi et al., 2018).

Similarly, Manjunatha & Dinesh (2013) sought to determine the effects of heat treatment and water quench age hardening on the microstructure, strength, and abrasive wear behaviour of certain aluminium alloys. The composites under consideration were aluminium 6061-based composited, specifically chosen owing to their increasing popularity in aerospace and industrial applications. This alloy was compared with another, which was reinforced using carbon nanotubes and the purpose was to establish which one performed better after heat treatment. Following quenching, the properties of both alloys were evaluated. Using micrographic studies, the authors demonstrated that hardness and abrasive wear-resistance of the reinforced composites were superior compared to their counterparts (Manjunatha & Dinesh, 2013).

Rakhimov et al. (2017) performed a similar study to evaluate the impact of certain heat treatment parameters on the properties of surface hardening. Their study was motivated by a necessity to constantly improve features such as power and performance for machines, which can be done by improving the performance of their individual parts. The metal under consideration in this study was steel. Using plasma treatment, the structural and surface properties of the hardened layer were evaluated. The stability parameters of the steel were determined to be positive, and the effectiveness of thermal hardening of the surface layer was recognized (Rakhimov et al., 2017).

Inoue et al. (2007) studied the hardening behaviour of dilute Mo-Ti alloys using a two-step heat treatment, which is represented in figure 3 below. Once the samples were carburized, changes in the surface hardness as well as the hardness of the metal all the way through to the center was compared with the hardness before heat treatment. Results from these experiments demonstrated that the hardness increased linearly with Ti content, prior to carburizing. Following the heat treatment, the region below the surface hard layer was also hardened due to the presence of Ti and C atoms. Such findings are useful to reiterate the importance of using certain alloys to achieve certain desirable hardness values.

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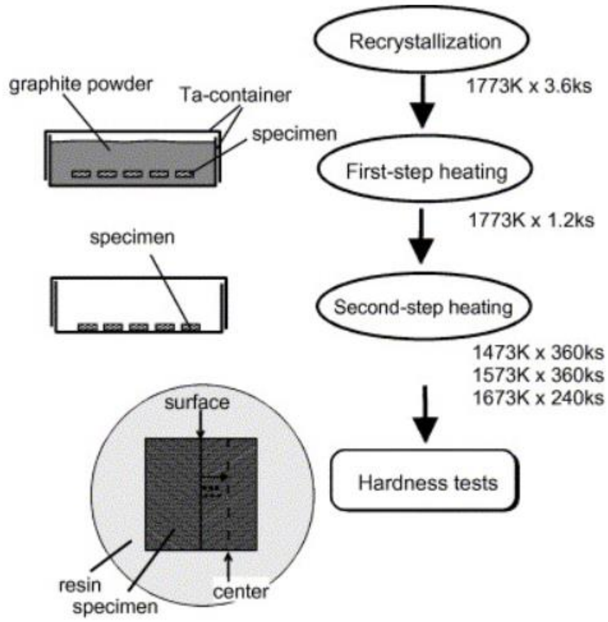


Figure 3: Two-step heat treatment (Inoue et al., 2007)

Rad & Lichter (2016) performed a heat treatment analysis of E110 case hardening steel, relying particularly upon mechanical and microstructural behaviour of the samples. Various heat treatment methods were employed, including quenching, normalizing, and tempering. Following heat treatment, the properties were analysed to show that quenching produced martensitic microstructures with demonstrated increases in the material's hardness. The annealed samples showed coarse pearlitic microstructures, with little improvements in hardness. The normalized samples showed a moderate increase in hardness. These findings indicate the superiority of certain heat treatment methods over others, for the case of E110 steel.

Ma et al. (2017) set out to investigate the microstructure and hardening behaviour of a certain type of modified steel known as BHSS. The primary purpose of the study was to distinguish whether addition of Al at certain concentrations would affect hardness of the material. Using characterization studies, the authors demonstrated that the material contained borides and dendrite martensite prior to Al addition. The addition of Al caused pearlite and ferrite to form, and when this sample was subjected to heat treatment, it caused a remarkable increase in the bulk hardness of BHSS, even during destabilized conditions. This is shown in the graph in figure 4 below. It was also observed that addition of Al caused precipitation hardening to occur. Such experiments are indicative of the potential for adding certain materials to improve hardness after heat treatment.

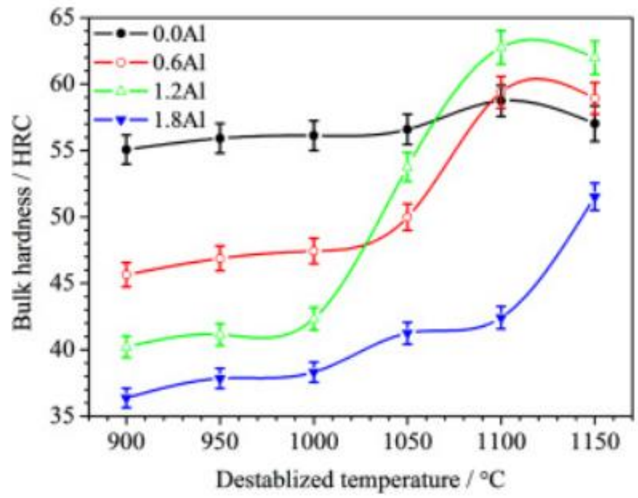


Figure 4: Al content and its relationship with bulk hardness (Ma et al., 2017)

## HEAT TREATMENT & HARDENING FOR TITANIUM ALLOYS

Titanium alloys are often popular materials in heat treatment and hardening studies, owing to their widespread utility in the aircraft industry. Military-grade materials are also made of titanium alloys. Desired mechanical properties of these alloys are achieved by optimizing the heat treatment process, and several authors have addressed this. Lee et al. (2017) considered a certain titanium alloy Ti-6Al-4V which was evaluated for its heat treatment parameters. Optimization of these heat treatment parameters was done using the Taguchi method. In particular, hardness and tensile strength were chosen as the parameters to evaluate. Controlled parameters included temperature, cooling rate and duration of treatment, amongst others. Results demonstrated that the optimal heat treatment conditions caused the best hardness in the alloy, and tensile strength was also drastically improved.

Akhonin et al. (2019) also performed a similar study to evaluate the properties of a titanium alloy using heat treatment, known as beta-titanium. In their analysis, the authors relied on different modes of heat treatment, including electron beam welding followed by furnace annealing, slow speed cooling, water quenching, and aging impact on welded joints of the metal. Results from this study suggested there was an inversely proportional relationship between the strength of the metal and the amount of beta phase present in the weld metal. When the beta phase was decreased from 91% to 53%, the strength of the welded joints increased from 876 MPa to 937 MPa. The authors further suggested that strength was increased optimally by using furnace annealing as the method of heat treatment, also done for the lower beta phase sample.

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Certain titanium alloys can be made to possess superior strength capabilities by adding small concentrations of oxygen into the alloy. Liu & Welsch (1988) conducted one of the earliest studies into this, and their purpose was to explore the effects of presence of oxygen as well as heat treatment on mechanical properties of alpha and beta titanium alloys. Using characterization techniques such as X-ray diffraction, microscopy and mechanical tests, the effects of these processes on the alloys were determined. It was shown that both alpha and beta alloys had increased hardness proportional to the oxygen concentration. Hardening for the alloys with oxygen content remained unchanged and mostly similar to the samples without oxygen. The ductility of the alpha sample was affected by aging, though not to a very large extent.

## Laser Beams for Heat Treatment

Davis et al. (1981) considered hardening of metal surfaces using heat emanated from scanning laser beams. The authors considered the CO2 laser for this purpose, given its high power density. To assess the feasibility of employing this process, the authors carried out analyses considering heat transfer (specifically, conduction). Using mathematical models, the authors were able to estimate the depth of hardening in steel exposed to scanning laser. Comparing their experimental results and modelling parameters, the authors found good agreement between the two and suggested scanning laser hardening to be yet another viable option for metal hardening using heat treatment (Davis et al., 1981).

The use of laser beams for metal hardening has been investigated by several authors. Moradi et al. (2019) considered diode laser surface hardening of AISI 410 stainless steel in order to draw a comparison with furnace hardening heat treatment. Physical experiments were performed to analyse the two processes, and the parameter for measurement was the microhardness of the surface layer that was hardened using laser. Optical microscopy and field emission scanning electron microscopy were also performed in order to elucidate metal properties. Microstructure images of the samples are shown in figure 5 below. The authors concluded that increasing laser power and decreasing scanning speed both caused the surface hardness and depth of hardness to increase, and that diode laser induced hardness 1.4 times that achieved through furnace hardening heat treatment. This suggests that newer technologies such as laser beams may be a better alternative for heat treatment (Moradi et al., 2019).

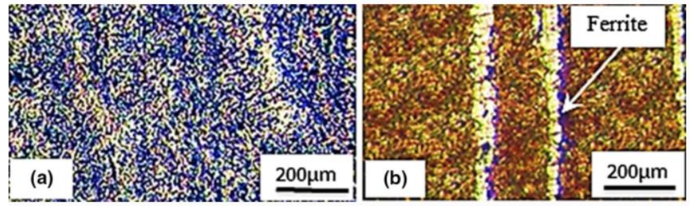

Figure 5: Microstructure images of samples subjected to (a) furnace heat treatment and (b) laser heat treatment (Moradi et al., 2019)

Bonss et al. (2006) conducted a unique study to explore integrated heat treatment for hardening of precise parts. Their research was motivated by a lack of existing methods to address hardening of smaller parts of a machine without significant costs and production times. The authors suggest that integrated heat treatment is a viable hardening method which is controlled by an offline programming system. Using a high-power diode laser, smaller parts can be heat treated for hardening without occurring very high costs or having to transport them back and forth between suppliers. Evidently, innovative hardening methods such as this one are gaining popularity owing to their substantial benefits.

Rodriguez et al. (1997) considered an environment-friendly alternative for surface hardening of steel using heat treatment. The authors relied on solar energy to provide the required power density for hardening steel. In a solar furnace, concentrated solar energy is attributed towards providing the required high temperatures for metal hardening. In their study, Rodriguez et al. (1997) performed surface hardening on CrMo4 steel, and the hardness properties were measured by analysing microstructure changes as well as metal hardness values.

Results from their study suggested that the hardened zone on the metal was somewhere between 1 mm and 10 mm deep, and this was achieved within 30 seconds of treatment (Rodriguez et al., 1997). Clearly, there are sustainable alternatives such as employing solar energy to treat metals for hardening, and they can be employed accordingly to reach specific hardness values similar to traditionally used heat treatment techniques.

Jeon et al. (2014) sought to investigate the hardening effects of pre- and post-firing heat treatment for a firing-simulated Au-Pd-In metal-ceramic alloy. The aim of the study was to determine whether additional post-firing heat treatment contributed to better hardening of the Au-Pd-In metal-ceramic alloy. It was also desired to compare the hardening of the material by drawing a comparison between the pre- and post-firing heat treatments. Using a series of physical experiments, the authors demonstrated the superior effectiveness of using post-firing heat treatment in adding to the hardening effect of the treatment. Moreover, prefiring treatment was demonstrated to cause weak hardening and the optimal results were

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achieved by omitting pre-firing and performing post-firing heat treatment only (Jeon et al., 2014).

To sum up, there are various types of heat treatment methods adopted by different academic researchers to meet certain goals. The purpose of each of the studies reviewed here was to study some type of heat treatment performed over certain metals and/or alloys and draw conclusions relating certain process or sample parameters to the hardness and other mechanical properties of treated samples.

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