IJCRT.ORG ISSN : 2320-2882

INTERNATIONAL JOURNAL OF CREATIVE RESEARCH THOUGHTS (IJCRT)

An International Open Access, Peer-reviewed, Refereed Journal

# Effect Of Heat Dissipation On The Final Properties Of Steel Upon Quenching: A Review

[1]Hemant Panchal, [*2]Moksha Patel, [2] Devanshi Bhaliya
[1]Assistant Professor, Metallurgical & Materials Engineering Department,
Faculty of Technology & Engineering, The M. S. University of Baroda, Vadodara
[2]Under Graduate Student, Metallurgical & Materials Engineering Department,
Faculty of Technology & Engineering, The M. S. University of Baroda, Vadodara

*Abstract:* In the ever evolving world of today where manufacturing sector is at a boost, the use of steel in recent times has gained paramount importance.As per the demand of consumers, various alterations can be made in the properties of steel by performing already known heat dissipation techniques and application can be well classified.Aim of the review is to collect the information about the effect of various heat treatments on the properties of steel especially the effect of quenching on the mechanical and physical properties of the steel.Along with quick cooling that is quenching, the review also highlights on the effect of other heat treatment processes like annealing, normalizing and tempering.The mechanical properties can easily be modified by heat treating the steel to suit a particular design purpose.In order to improve the properties, the steels have to be heat treated. The paper include the effect of the heat treatment on some properties of steel such as tensile strength, percentage elongation, micro-hardness, ultimate tensile strength, Grey relation co-efficient, fatigue characteristics, hardness test, micro-structure study, chemical composition, yield strength, impact energy, S-N behaviour, wear rate, toughness.The paper include the effect of the properties of steel in different quenching media such as water, oil, brine solution, etc.

*Index Terms* - Heat treatment, Steel, Mechanical properties, Quenching, Tempering

## I. Introduction

A combination of heating and cooling processes used to a metal or alloy in its solid state to achieve desired conditions or qualities is known as heat treatment.[1] Heat treatment is a combination of controlled heating and cooling of a metal or alloy in the solid state in a per-determined way to produce a desired microstructure and desired mechanical properties. Many structural applications are associated to steel.[2] Engineering materials, mostly steel, are heat treated under controlled sequence of heating and cooling to alter their physical and mechanical properties to meet desired engineering applications.[3] The heat treatment of steel under controlled conditions alters their physical and mechanical properties, enabling them to meet the desired engineering applications.[4] In order to enhanced mechanical properties, the steel has to be heat treated with different processes.[5] Different heat treatment processes gave different hardness value and impact property to the steel.[6] Heat treatment of steel slightly affects other properties such as its ability to conduct heat and electricity as well.[7]

Steel is an alloy of iron with varying percentage of carbon ranging from 0.15-1.7%. and manganese. Mainly it is classified into five types: i) carbon steel, ii) alloy steels, iii) stainless steels iv) tool steels and v)Special-purpose steels. Carbon steel is further classified into 3 groups : a) Low carbon steel (<0.3 %C), b) Medium carbon steel (0.3-0.6 %C) and c) High carbon steel (0.6-1.7 %C).[8,9]

Carbon is an effective, cheap, hardening element for iron and hence a large tonnage of commercial steels contains very little alloying element.[10] Steel is the most important and versatile engineering alloy. It finds numerous applications.[11,12] Carbon steels have wide applications in oil and gas pipelines, power plant components and armour structures due to their good mechanical properties.[13] These steels are mainly used for making shafts, axles, gears, crankshafts, couplings, forgings and multitude of machine parts.[10,14]
As we know iron has allotropic transformation. So that various phases are present at different temperature and different composition in steel , which can be study using phase diagram, which involves leisurely heating and cooling.A phase diagram is a graphical representation of the equilibrium temperature and composition limits of phase fields and phase reactions in an alloy system. [8]

1.1 Designation

In 1941, the EN range of steel specifications was first introduced as the War Emergency Numbering. This was also known as the British Standard Schedule BS970.The ‘Technical Advisory Committee’ of the ‘Special & Alloy Steels Committee’,aided the British Standards Institute who then published 58 steel specifications (EN 1 to EN 58).Carbon steels, alloy steels, case hardening steels, spring steels and stainless steels were all detailed in this publication.The higher the EN number, the better the quality of steel and the more carbon, or blended elements, are added to the chemical content.It is often found that a further letter is added to the EN number to indicate a heat treated condition, more commonly used among the higher carbon steels to denote the hardness state.

EN1 to EN3 - Low carbon, general purpose steel.
EN5 to EN16 – Medium carbon content with general purpose strength.
EN19 to EN24 – Higher carbon steels with good hardenablity.
EN32 to EN36 – Hard wearing materials.
EN40 to EN45 – Spring steels.
EN56 to EN60 – Stainless steels.

The below table gives the designation of AISI standard. In that the first digit indicates the primary alloying element, the second digit reflects the type and amount of the other alloying elements, and the last two digits indicate the carbon content in hundredths of a percent.

Table 1.1: Nomenclature for Steel

| AISI Designation | Type |
|---|---|
| 1XXX | Carbon steels |
| 2XXX | Nickel steels |
| 3XXX | Nickel-Chromium steels |
| 4XXX | Molybdenum steels |
| 5XXX | Chromium steels |
| 6XXX | Chromium-Vanadium steels |
| 7XXX | Tungsten steels |
| 8XXX | Nickel-Chromium-Vanadium steels |
| 9XXX | Silicon-Manganese steels |

1.2 Heat dissipation of Steel

The properties of steel are related to its structural make-up. The desired levels of mechanical properties can be obtained by altering the size, shape and distribution of various constituents. This is achieved in practice by the process of heat treatment/dissipation. Heat treatment plays an important role in such a wide acceptance of steel as an engineering material. Properties of steel can be controlled and varied over a very wide range by heat treatment. [11,12]
Various heat treatment processes which are applicable for carbon steel are as follow:

1. Stress relieving
2. Annealing
3. Spherodizing
4. Normalizing
5. Hardening
6. Tempering
7. Austemering
8. Martempering
9. Sub-zero treatment
10. Patentin

## II. Effect of Quenching

Quenching is one of the major processes of heat treatment of carbon steel that aims at improving its mechanical properties. The process of improving the mechanical properties of carbon steel by varying some key factors like the quenchant used, heat treatment temperature, and soaking time.[15]
The quenching media is the most significant factor affecting the Heat Treatment with a percentage contribution of 95.66%.[16] The hardness of treated steel is directly proportional to the rate of cooling.[17]
The annealed samples with mainly ferrite structure gave the lowest tensile strength and hardness value and highest ductility and toughness value while hardened sample which comprise martensite gave the highest tensile strength and hardness value and lowest ductility and toughness value.[3] Toughness of air quenched sample is lower than water quenched and oil quenched sample but higher than annealed sample and oil quenched sample has the highest toughness.[18]
Annealed sample has lowest tensile strength, hardness and yield strength whereas highest toughness, percentage elongation and percentage reduction and higher young modulus than untreated one and normalized. Hardened sample has highest tensile strength, hardness, yield strength and young modulus whereas lowest toughness, percentage elongation and percentage reduction.Tempered and normalized samples have overall intermediate properties.[3]
Thus, we can say that quenched sample has highest mechanical properties compare to other heat treatments.

### 2.1 Effect of quenching on the micro-structure

The Metallographic examination revealed the accurate characteristic of the steel Sample.[13] The choice of quenching method has a significant impact on the micro-structure and consequently, the mechanical properties of a material.[10] Water quenching is used when high hardness is required, but it often sacrifices toughness. Oil quenching offers a compromise between hardness and toughness, while air cooling results in a micro-structure with good toughness but lower hardness. The specific micro-structure achieved also depends on factors such as the composition of the material, initial temperature and the quenching process parameters.[19,20,21]

### 2.2 Effect of quenching on properties of steel

In materials science and metallurgy, the relationship between various properties and behaviors of materials is of paramount importance. Generally, a higher hardness corresponds to a lower wear rate, while the wear rate tends to increase with applied load.[18] Enhanced dispersion within the material is associated with increased hardness. In some cases, such as with hardened and tempered specimens, the percentage of peak elongation can be significantly greater than in other conditions, indicating improved ductility at the point of failure. However, it's important to note that as tempering temperature and time increase, the ultimate tensile strength may decrease, along with some reduction in yield strength, while elongation generally increases. One notable case is conventional hardening, which results in the highest hardness due to the formation of a martensite structure.[2,5,17,22]
When comparing different heat treatment methods, tempered samples often exhibit higher ultimate tensile strength but lower ductility, whereas stress-relieved samples show greater elongation compared to normalized specimens. In terms of failure load and tensile strength, the order typically follows as bought < stress relieved < normalized < hardened & tempered.[5,23] For specific materials like EN 31 and EN 8, the effects of heat treatment become evident. After annealing, the material becomes softer compared to its untreated state. In contrast, normalizing results in higher hardness. However, it's during hardening and tempering that the specimen becomes the hardest among the tested conditions due to the formation of fine-tempered martensite. In another example with D3 steel, the post-heat-treated specimens not only exhibit high hardness but also demonstrate good corrosion resistance.[16]
In fatigue analysis of medium carbon steels like EN 8, fatigue failure is a significant concern, with plastic deformation occurring more in weaker phases and generating higher stresses in stronger phases. The fatigue strength hierarchy typically follows the order: Not treated < Annealed < Normalized < Tempered. Reducing the tempering temperature can increase fatigue strength and other properties, such as the Factor of Safety (FOS) for the material.[24] Where water quenching and closed-oil quenching result in comparable hardness levels, both exceeding the raw material. Water quenched material tends to exhibit the best mechanical properties in terms of hardness among various quenched materials.[25]
*Hardening and Micro-Hardness:* Hardening involves heating the material to a critical temperature and then rapidly cooling it, often through quenching in water, oil, or other mediums. This rapid cooling creates a

micro-structure that can be significantly harder than the original material. Micro-hardness typically increases after hardening due to the formation of harder phases, such as martensite.[10,26]

*Tempering and Micro-Hardness:* Tempering is a heat treatment process that follows hardening. It involves reheating the hardened material to a lower temperature and then cooling it again. Tempering is used to reduce brittleness and improve toughness. While the overall hardness may decrease slightly during tempering, micro-hardness can remain relatively high due to the presence of residual hard phases like tempered martensite.[10,26]

Water quenched offers the highest wear resistance but comes with a higher risk of quench cracking and limited toughness. Oil quenched provides a balance between wear resistance and toughness, making it suitable for various applications. Air cool prioritizes toughness and reduced risk of distortion over wear resistance and may not be suitable for high-wear applications.[1] Water quenched offers high wear resistance but typically results in lower impact energy due to its brittle martensitic micro-structure. Oil quenched provides a balance between wear resistance and impact toughness, making it suitable for applications requiring both properties. Air cooled prioritizes impact energy and toughness over wear resistance and may be suitable for applications with high impact loading.[7]

The exact relationship between percentage elongation and heating temperature after quenching depends on various factors, including the steel's composition, specific heat treatment process parameters, and the desired material properties for the intended application.

To determine the precise effect of different quenching media on percentage elongation with heating temperature, experimental testing and analysis using specific medium carbon steel compositions and quenching conditions would be necessary.[10,22]

Water quenched results in increased hardness at higher heating temperatures due to rapid cooling. Oil quenched provides balanced hardness levels across a range of heating temperatures. Air cooled yields lower hardness levels compared to rapid quenching methods.[5]

The S-N curves for different quenching media will exhibit distinct characteristics. Water quenching may show higher endurance limit but lower fatigue life at lower stress levels due to its brittle microstructure. Oil quenching tends to offer a more balanced performance, while air cooling can provide improved fatigue resistance.[13]

## III. Testing Methods

The Taguchi method and Grey relational analysis have both been employed to investigate the optimization of mechanical properties, including hardness, yield strength, and ultimate tensile strength, in medium carbon steel subjected to various quenching media. These analyses consistently identified soaking time as the primary process parameter with the highest contribution ratios.[15,16] In a related study utilizing the Taguchi method, the primary objective was to maximize the hardness of steel through heat treatment. It's well-known that an increase in carbon content leads to improved material hardness and strength. By applying Taguchi and ANOVA techniques, researchers aimed to identify the optimal parameters for the heat treatment process.[15,16]

An additional consideration when choosing a quenching medium is the potential for gas absorption. Water quenching has the drawback of absorbing substantial atmospheric gases. When hot metal is quenched in water, these gases tend to form bubbles on the metal surface.[27] These bubbles can accumulate in recesses and create soft spots that may later result in cracking or warping of the material. As a result, the Tensile Test confirmed that oil quenching is a preferable choice for EN 31 steel.[15,16].

## IV. Summary

Steel's mechanical properties vary with different heat treatment processes. Notably, hardened and tempered steel excels in ductility, displaying a significant percentage peak elongation. When it comes to failure load and tensile strength, the sequence progresses from the as-bought state to stress-relieved, normalized, and peaks in the hardened and tempered state. A similar trend is observed in fatigue strength, with untreated steel having the lowest fatigue strength, followed by annealed, normalized, and tempered conditions. Steel hardness correlates with the cooling rate during heat treatment, with faster cooling resulting in higher hardness levels. For applications emphasizing strength and hardness, hardening is recommended. Impact energy measurements favor water-quenched (WQ) steel over oil-quenched (OQ) steel. Regarding hardness, various quenching media rank as follows: furnace cooling < air cooling < oil cooling < hot water cooling <

cold water cooling < cold brine solution cooling. It's worth noting that while hardened steel exhibits the highest tensile strength and hardness, it sacrifices some ductility compared to other conditions.

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