Chapter

Strengthening of High-Alloy Steel through Innovative Heat Treatment Routes

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Abstract

Heat treatment route is an important route for the development of high-strength alloy steel. Many heat treatment processes are applied depending on alloy compositions and desired mechanical properties. There are various high-strength alloy steels, namely, austenitic stainless steel (16–26 wt%Cr, 0.07–0.15 wt%C, 8–10 wt%Ni, rest Fe), where the heat treatment adopted is the low-temperature plasma nitriding so as to achieve a strength in a range of 800–1000 MPa. In twinning-induced plasticity (TWIP) steel (>20 wt%Mn, <1 wt%C, <3 wt%Si, <3 wt%Al, rest Fe), high-temperature thermomechanical heat treatment provides a strength greater than 1000 MPa. High-speed steel (18 wt%W, 4 wt%Cr, 1 wt%V, 0.7 wt%C, 5–8 wt%Co, rest Fe) suits best for high-speed machining purpose, owing to secondary hardening. Besides, high-temperature annealing is performed with majorly ferritic structure to achieve a maximum bending strength of 4700 MPa. Furthermore, in Hadfield steel (11–14 wt%Mn, 1–1.4 wt%C), a fully austenitic phase is obtained with a strength level of 1000 MPa. High-alloy tool steel (5 wt%Mo, 6 wt%W, 4 wt%Cr, 0.3 wt%Si, 1 wt%V, rest Fe) is provided with austenitizing, quenching, and tempering treatment to achieve a maximum hardness of 1200–1400 HV.

Keywords: high alloy steel, heat treatment, strengthening mechanism, mechanical properties

1. Introduction

Steel, because of its numerous applications, is the most important material among any engineering materials. It is mostly used in tools, automobiles, buildings, infrastructure, machines, ships, trains, appliances, etc., due to its low cost and high tensile strength. Primarily, steel is an alloy of iron and carbon, along with some other elements. The prime material of steel is iron. Iron is commonly found in the Earth's crust in the form of ore, generally an iron oxide, i.e., magnetite or hematite. The extraction of iron from iron ore is done by removing oxygen and then reacting it with carbon to form carbon dioxide. This process is called smelting. Iron has the ability to have two crystalline forms, i.e., face-centered cubic (FCC) and body-centered cubic (BCC), depending on the operation temperature. Fe-C mixture is also added with other elements to produce steel with enhanced properties. Manganese and nickel (Ni) in steel are added to increase its tensile strength and promote stable austenite phase in Fe-C solution, chromium (Cr) increases hardness and melting temperature, and titanium (Ti), vanadium (V), and niobium (Nb) also increase the hardness. There are two types of steel depending on the alloying elements. If the alloying elements are above 10%, it is referred to as high-alloy steel, and in case of alloying element with 5–10%, it is referred to as medium-alloy steel. If the alloying element in the steel is below 5%, it is called low-alloy steel. The density of steel varies from 7.1 to 8.05 g/cm^3 according to the alloying constituents.

When 0.8% of carbon-contained steels (identified as a eutectoid steel) are cooled, austenitic phase (FCC) of the combination tries to revert to the ferrite phase (BCC). The carbon is no longer contained in the FCC austenite structure, which causes excess of carbon. The alternative method to remove carbon from austenite is the precipitation of the solution like cementite and parting behind a neighboring phase of ferrite BCC iron with small quantity of carbon. A layered structure called pearlite is produced when the two, ferrite and cementite, precipitate at the same time. In case of hypereutectoid composition (>0.8% carbon), the carbon will predominantly precipitate out in the form of large inclusions of cementite on the austenite grain boundaries until the amount of carbon in the grains has reduced to the eutectoid composition (0.8% carbon), at which stage the pearlite formation takes place. For steels that have less than 0.8% carbon (called hypoeutectoid), it results in ferrite formation initially in the grains unless the residual content reaches 0.8%, at which stage pearlite formation takes place. No bulky cementite inclusion occurs in the boundaries in hypoeutectoid steel. The cooling process is assumed to be very slow due to the above reasons, hence letting adequate time for the transmission of carbon. Increased rate of cooling does not allow the carbon to migrate for the formation of carbide in the grain boundaries. Rather it will form large amount of finer structure pearlite; hence the carbide is further extensively dispersed and performs to prevent slip of defects inside those grains, ensuing in hardening of the steel. At very high rate of cooling, the carbon has no time to transfer; as a result it is confined inside the austenite and transforms to martensite. The martensite phase is the supersaturated type of carbon, the most strained as well as stressed phase which is exceptionally hard although brittle. Considering the carbon content, the martensite phase obtains various forms. Carbon below 0.2% obtains a ferrite (BCC) form, whereas at higher level of carbon, it acquires a body-centered tetragonal (BCT) structure. Thermal activation energy is not acquired for the conversion from austenite into martensite.

Martensite has a lesser density (as it expands at the time of cooling) than austenite does. As a result the conversion among them consequences a variation in amount. During the above process, growth occurs. Internal stresses as of this growth usually acquire the compressed crystal form of martensite and elongated form on the left over ferrite, along with a significant quantity of shear on the constituents. When quenching is not appropriately done, it can cause crack on cooling due to the internal stresses in a part. They cause interior work hardening and other microscopic imperfections. It is ordinary for quench cracks to appear when steel is water quenched, even though they may not always be visible.

2. Role of major alloying element in steel

2.1 Carbon

The carbon steels are composed of carbon and iron by means of carbon up to 2.1 wt%. At the same time, when the carbon content increases, steel has the capability to become harder as well as stronger by heat treating, though it undergoes less ductility. In spite of heat treatment, a higher carbon content also decreases weldability. In carbon steels, the higher carbon content lowers the melting point.

The classifications of carbon steel are on the basis of carbon content:

Low-carbon steel: carbon wt% is in the range of 0.05–0.30 (called plain carbon steel) [1].

Medium-carbon steel: 0.3–0.6% is the approximate carbon content [1]. It helps in balancing ductility and strength and also has superior wear resistance; it is used in automobiles [2, 3].

High-carbon steel: carbon content lies from 0.60 to 1.00% [1]. It has very high strength and is used for tools, edged tools, springs, and wires [4].

Ultrahigh-carbon steel: it has carbon% between 1.25 and 2.0 [1]. It can be tempered to immense hardness. It is used in various purposes like axles, punches, or knives.

2.2 Detailed study of low- and high-carbon steel

2.2.1 Mild- or low-carbon steel

Mild steel, well known as plain carbon, is at present the common variety of steel as it is cost-effective and offers material properties for a lot of applications. It contains carbon wt% in the range of 0.05–0.30, building it more malleable and ductile. It has comparatively low tensile strength, other than being contemptible and simple to produce; surface hardness can be improved by carburizing. Due to its ductile nature, the failure from yielding is less risky, so it is best applicable (e.g., structural steel). The density of mild or low steel is ~7.85 g/cm^3 [5] and Young's modulus is ~200 GPa [6]. Low-carbon steels include a smaller amount of carbon than other steels and are easy to handle as it is more deformable.

2.2.2 Higher-carbon steels

Carbon steels that successfully experience heat treatment contain carbon in between 0.30 and 1.70 wt%. The impurities of different elements also have a considerable consequence on the superiority of the ensuing steel. Small amount of sulfur content makes steel brittle and crumble on operational temperatures. Manganese is added to enhance the hardenability of the steels. The name "carbon steel" can be employed in terms of the steel that is not stainless steel; in addition to it, carbon steel can be involved in alloy steels. Current modern steels are prepared with various mixtures of alloying elements to execute in various applications. The steel is alloyed along with additional elements, typically manganese, molybdenum (Mo), nickel, or chromium up to 10 wt%, in order to develop the hardenability. High-strength low-alloy steel has small additions (<2 wt%) of added elements, usually 1.5 wt% manganese, to offer extra strength.

3. Alloying elements and their effects on steels

Alloy steel reflects a category of steel facilitated with the addition of different elements. In general, all steels are referred to as alloy steel, while the plain steel is composed of iron added up to 2.06 wt% carbon. However, the term "alloy steel" commonly refers to steels that are alloyed with elements other than carbon. The total wt% of the alloying elements can be up to 20% to provide the material enhanced properties like better wear resistance, strength, or ductility. Low-alloyed steels are distinguished by their lower content of alloys with total content below 5%, whereas in the case of high-alloyed steel, the total sum of elements can be in the range of 5–20%, with improved properties. Apart from the above alloyed steels, there are even unalloyed steels that carry very small quantity of alloys. High-alloyed steel contributes to high strength, toughness, hardness, and creep resistance at specific heat treatment temperature. It also advances machinability and corrosion resistance. In addition, it even strengthens the properties of other alloying elements.

3.1 Austenite-stabilizing alloying element

The accumulation of certain alloying elements, such as manganese and nickel, can stabilize the austenitic structure, facilitating heat treatment of low-alloy steels. In the extreme case of austenitic stainless steel, much higher alloy content makes this structure stable even at room temperature. On the other hand, such elements as silicon, molybdenum, and chromium tend to destabilize austenite, raising the eutectoid temperature.

Austenite is only stable above 910°C (1670°F) in bulk metal form. However, FCC transition metals can be grown on a face-centered cubic or diamond cubic [7]. The epitaxial growth of austenite on the diamond (100) face is feasible because of the close lattice match, and the symmetry of the diamond (100) face is FCC. More than a monolayer of γ-iron can be grown because the critical thickness for the strained multilayer is greater than a monolayer [7]. The determined critical thickness is in close agreement with theoretical prediction.

As the names suggest, austenite stabilizers are elements, which make austenite (of iron) stable at lower temperature, that would occur in pure iron. With enough amount of austenite stabilizer, you can have austenite stable at room temperature. Effectively, they decrease the austenitizing temperature of iron, in the Fe-C diagram.

Examples: Mn, Ni, C etc.

Manganese: in alloy steel, manganese is typically used in combination with sulfur and phosphorus. Manganese helps reduce brittleness and improves forgeability, tensile strength, and resistance to wear. Manganese reacts with sulfur, resulting in manganese sulfides which prevent the formation of iron sulfides. Manganese is also added for better hardenability as it leads to slower quenching rates in hardening techniques. Excess oxygen can be removed in molten steel by using manganese.

Nickel: austenitic stainless steels are most known for their high content in nickel and chromium. It is used to increase strength, hardness, impact toughness, and corrosion resistance. Nickel-alloyed steels are often found in combination with chromium, resulting in an even higher hardness.

3.2 Ferrite-stabilizing alloying element

By decreasing eutectoid composition and increasing eutectoid temperature, ferrite stabilizers are the elements which stabilize ferrite phase. Cr and Si are examples for ferrite stabilizers. Ferrite stabilizers are also called carbide former element. **Stabilizing ferrite** decreases the temperature range, in which austenite exists.

The elements, with the same crystal structure as that of ferrite (body-centered cubic—BCC), increase the A_3 temperature and lower the A_4 point. An increase in the amount of carbides in the steel is caused by decreasing the solubility of carbon in austenite by these elements. The following elements have ferrite-stabilizing effect: chromium, tungsten (W), aluminum (Al), molybdenum, silicon, and vanadium. Examples of ferritic steels are transformer sheet steel (3% Si) and F-Cr alloys.

Chromium: chromium is one of the most common alloying metals for steel because of its high hardness and corrosion resistance. Pure chromium is a gray, brittle, and hard metal with a melting point of 1907°C (3465°F) and a high-temperature resistance. In steel, hardenability is increased by the alloying chromium. Higher chromium contents up to 18% result in enhanced corrosion resistance. For example, stainless steel, which is one of the most popular steel alloys, uses at least 10.5% chromium, enhancing its resistance against water, heat, or corrosion damage. Chromium oxide does not spread and fall away from the material in contrast to iron oxide in unprotected carbon steel. It creates a film of dense chromium oxide on the surface that blocks out any further corrosion attacks.

Molybdenum: it is a silvery-white metal that is ductile and highly resistant to corrosion. It has one of the highest melting points of all pure elements—together with the elements tantalum (Ta) and tungsten. **Molybdenum** is also a micronutrient essential for life.

3.3 Carbide-forming alloying elements

Carbide-forming elements form hard carbides in steels. Steel hardness and strength are increased by hard (often complex) carbides formed by the elements like tungsten, niobium, molybdenum, chromium, vanadium, titanium, zirconium (Zr), and tantalum. Examples of steels containing relatively high concentration of carbides are high-speed steel and shot work tool steels. During reaction with nitrogen in steel, carbide-forming elements also form nitrides.

Tungsten is a rare metal found naturally on the Earth almost exclusively combined with other elements in chemical compounds rather than alone. It was identified as a new element in 1781 and first isolated as a metal in 1783. Its important ores include wolframite and scheelite.

The free element is remarkable for its robustness, especially the fact that it has the highest melting point of all the elements discovered, at 3422°C (6192°F, 3695 K). It also has the highest boiling point, at 5930°C (10,706°F, 6203 K). Its density is 19.25 times that of water, comparable to that of uranium and gold, and much higher (about 1.7 times) than that of lead. Polycrystalline tungsten is an intrinsically brittle and hard material (under standard conditions, when uncombined), making it difficult to work. However, pure single-crystalline tungsten is more ductile and can be cut with a hard steel.

4. Evolution of high-alloy steel

Alloy steel is added with a choice of elements in total amounts between 10 and 50 wt% to expand its mechanical properties. Alloyed steels are categorized into two groups: low- and high-alloy steels. The simplest form of steel is iron with carbon alloy (~0.1–1%). Common alloying elements comprise manganese (the most frequent one), chromium, nickel, molybdenum, silicon, aluminum, vanadium, titanium, niobium, and boron (B). Alloyed steels have improved properties such as strength, hardenability, toughness, hardness, wear resistance, corrosion resistance, and hot hardness [8]. To achieve these better-quality properties, the metal may require various heat treatment processes. Several of these are utilized in highly requiring applications, like in the turbine blades used in jet engines, in nuclear reactor, in spacecraft, etc. Iron, owing to its ferromagnetic nature, discovers major applications wherever the response to magnetism is important, like in transformers and electric motors.

4.1 Categorization of alloy steel and their heat treatments

Alloy steels are categorized into low- and high-alloy steels. High-alloy steels would be more than 10 wt% of alloying elements in steel groups [1, 5, 8, 9]. The majority of alloy steels lie under the group of low alloy. The most common alloy elements include chromium, manganese, nickel, molybdenum, vanadium, tungsten, cobalt, boron, and copper.

4.1.1 Low-alloy steel

Low-alloy steels are a group of ferrous materials that show improved mechanical properties compared to plain carbon steels, because of the alloying elements such as nickel, molybdenum and chromium. Through the development of specific alloys, low-alloy steel provides desired mechanical properties. Microstructure consists of ferrite and pearlite. Its properties are relatively soft and weak, although they have high ductility and toughness. Its various applications are auto-body components, structural shapes, sheets, etc. [2, 3, 5, 6, 10–12].

Some of the compositions of low-alloy steels are the following:

Cr 0.50% or 0.80% or 0.95%, Mo 0.12% or 0.20% or 0.25% or 0.30%, rest Fe

Mo 0.20% or 0.25% or 0.25% Mo or 0.042% S, rest Fe

Mo 0.40% or 0.52% C, rest Fe
Ni 1.82%, Cr 0.50% to 0.80%, Mo 0.25% Cu, rest Fe
Several low-alloy steels underwent normalizing and tempering in the manufacturing industries; however there is an increase affinity to a quenching and tempering action. Low-alloy steels are weldable, but pre-welding or post-welding heat treatment is essential to evade weld zone cracking issues.

4.1.2 High-alloy steels

In high-alloy steel, the entire alloying element content is above 10 wt%. In stainless steels, the principally alloying element is Cr (≥11 wt%). It is greatly resistant to corrosion. Nickel and molybdenum addition adds to corrosion resistance. An important property of the highly alloyed steel is the capability of alloying elements to promote the creation of a certain multiple phases and stabilize it. These elements are grouped into four major classes as discussed in the previous section: (1) austenite-forming, (2) ferrite-forming, and (3) carbide-forming.

Some varieties of the high-alloy steels are the following:

a. Stainless steels: Fe-18Cr-8Ni-1Mn-0.1C characteristically is γ-alloy. It stabilizes austenite for its rising temperature range, where austenite subsists. It elevates the austenite-forming temperature (A1) and reduces the A3 temperature. Mostly, this type of steels underwent solution annealing type of heat treatment primarily specified for austenitic stainless steels. The main requirement for this treatment is to dissolve all the precipitated phases, mainly chromium-rich carbides, where the precipitate of $M_{23}C_6$ occurs in the range of 673–1173 K. For other stainless steels, it is recommended to maintain the solution annealing temperature in the range of 1273–1393 K.

b. Tool steel: it provides necessary hardness with simpler heat treatment and retains hardness at high temperature. The primary alloying elements are Mo, W, and Cr. These elements have wear resistance, high strength, and toughness but have low ductility. One of the primary heat treatments provided for tool steel is tempering that requires cautious preparation. Various complex tool steels like the high-speed steel need twice over tempering to convert austenite to martensite completely. High-speed steel (18 wt%W, 4 wt%Cr, 1 wt%V, 0.7 wt%C, 5–8 wt%Co, rest Fe) suits best for high-speed machining purpose, owing to secondary hardening. Besides, high-temperature annealing is performed with majorly ferritic structure to achieve a maximum bending strength of 4700 MPa. These types of steels achieve utmost hardness after first tempering, which is followed by second tempering that lowers the hardness to the desired working level. In some cases, the third temper is needed for secondary hardening of steels to make sure that some new martensite produced as a consequence of austenite conversion in tempering is efficiently tempered. This is a subject of individual selection and includes minimum extra cost.

c. High-entropy alloy steel: the essential elements of the high-entropy steels are Fe, Co, Ni, Cr, Cu, and Al. The cast microstructure expands from FCC to BCC phase along with the increase in Al content. The hardness in BCC phase is greater than FCC phase; in addition to it, the corrosion resistance is also superior in BCC phase. Some of the high-entropy alloy steels like Al-Fe-Cr-Co-Ni-Ti alloy coating was equipped by laser cladding, and the effects of annealing temperature (873, 1073, and 1473 K) on structure and its properties were studied. The consequences illustrate that the intermetallic precipitation compounds in the coating are efficiently repressed through laser cladding by means of fast solidification, and the microstructure of the coating forms dendrite structure of BCC, having superior hardness (~698 HV). As a result, the grain size of the coating rises somewhat, and the microhardness reduces slightly, following various annealing temperatures at a range of 1073–1373 K. This specifies that the elevated temperature stability of the structure and microhardness of the coating are superior. Al and Fe are improved in dendritic boundary, while Co, Ni, Ti, and Cr are enhanced in interdendritic boundary. In addition, the degree of segregation rises with the enhancement of annealing temperature.

d. Twinning-induced plasticity (TWIP) steel: in TWIP steel (>20 wt%Mn, <1 wt%C, <3 wt%Si, <3 wt%Al, rest Fe) high-temperature thermomechanical heat treatment provides a strength greater than1000 MPa. The examination of the solution heat treatment of hot-rolled TWIP steel of the three various compositions (Fe-30Mn-3Si3Al, Fe-25Mn-4Si-2Al, and Fe-30Mn-4Si-2Al) reflected that prolonging the time of holding temperature can enhance the elongation through no change observed in strength. Prolonging the holding time facilitates both the production of additional annealing twins to amplify their areas of boundary and the boost in the number of twin boundaries that are favorable for the corrosion resistance creep and fracture.

e. Hadfield steel: in Hadfield steel (11–14 wt%Mn, 1–1.4 wt%C), a fully austenitic phase is obtained with a strength level of 1000 MPa. High-alloy tool steel (5 wt%Mo, 6 wt%W, 4 wt%Cr, 0.3 wt%Si, 1 wt%V, rest Fe) is provided with austenitizing, quenching, and tempering treatment to achieve a maximum hardness of 1200–1400 HV. The heat treatment processing of Hadfield manganese steel means dissolving the carbide precipitates at higher temperature, followed by fast cooling to attain austenitic carbide-free grains which is desired to be the preferred microstructure for the commercial applications.

5. Innovative heat treatment (processing)-structure–property correlation in high-alloy steel

High-temperature homogenization, complete annealing, normalizing, tempering, etc. are the usual methods in heat treatment process of steel. But there are certain modified ways of processing routes in order to enhance the mechanical properties [13–31]. The main objective of heat treatment in steel is to upgrade the mechanical properties like strength, toughness, impact resistance, etc. It is to be noted that thermal and electrical conductivities are changed to some extent, whereas Young's modulus remains unchanged. Iron has a better solubility for carbon in the austenitic phase, so the steel is heated at which the austenite phase persists.

Some of the newly introduced high-alloyed steels like TWIP steel show excellent mechanical properties, depending on the adoption of advanced heat treatment processes. In some processes the fabricated steels are first homogenized to ~1373 K for 1 hour, followed by hot rolling at 1273 K. The steels are then cooled in the furnace and then rolled at room temperature (as shown in **Figure 1**). Due to the above heat treatment, the presence of duplex phases of austenite and ferrite is observed. The rolling effect contributes in grain size reduction and hence helps in enhancing the strength of the steel. Additionally, due to the high-temperature rolling, there is also an occurrence of twins on the austenitic grains that also increases the strength of the metal. The above modification in the microstructure resulted in the improved tensile properties with 1000 MPa ultimate tensile strength and up to 60% elongation [13].

Recently, Mazaheri et al. suggested a cold rolling, followed by various intercritical annealing techniques for the production of ultimate ultrarefined-grained steel [22]. The microstructure contains ferrite-martensite duplex steel with excellent mechanical properties. In this processing route, the fabricated steel was first heated to austenitizing temperature, i.e., 880°C for 1 hour. Then it was annealed intercritically at ~770°C for 100 minutes trailed by water quenching (as shown in **Figure 2**). The steel was water cooled to acquire the desired microstructure of ferrite and

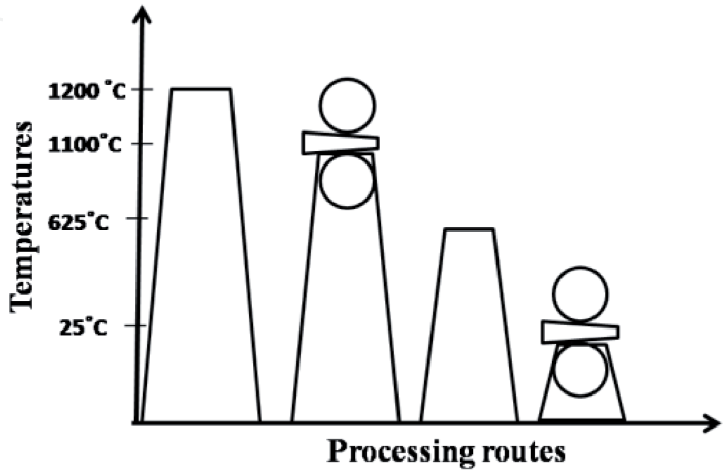

Figure 1.
Illustrating the processing routes of TWIP steel.

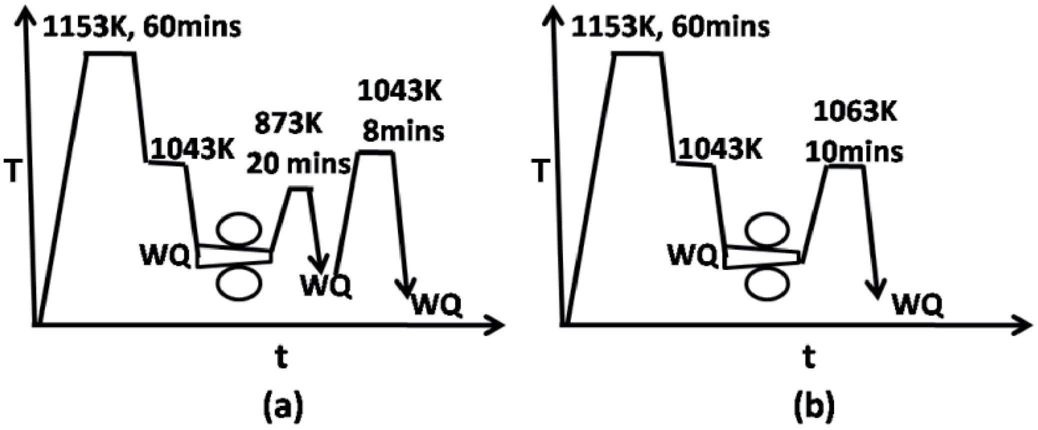

Figure 2.
Thermomechanical processing routes of dual-phase steel.

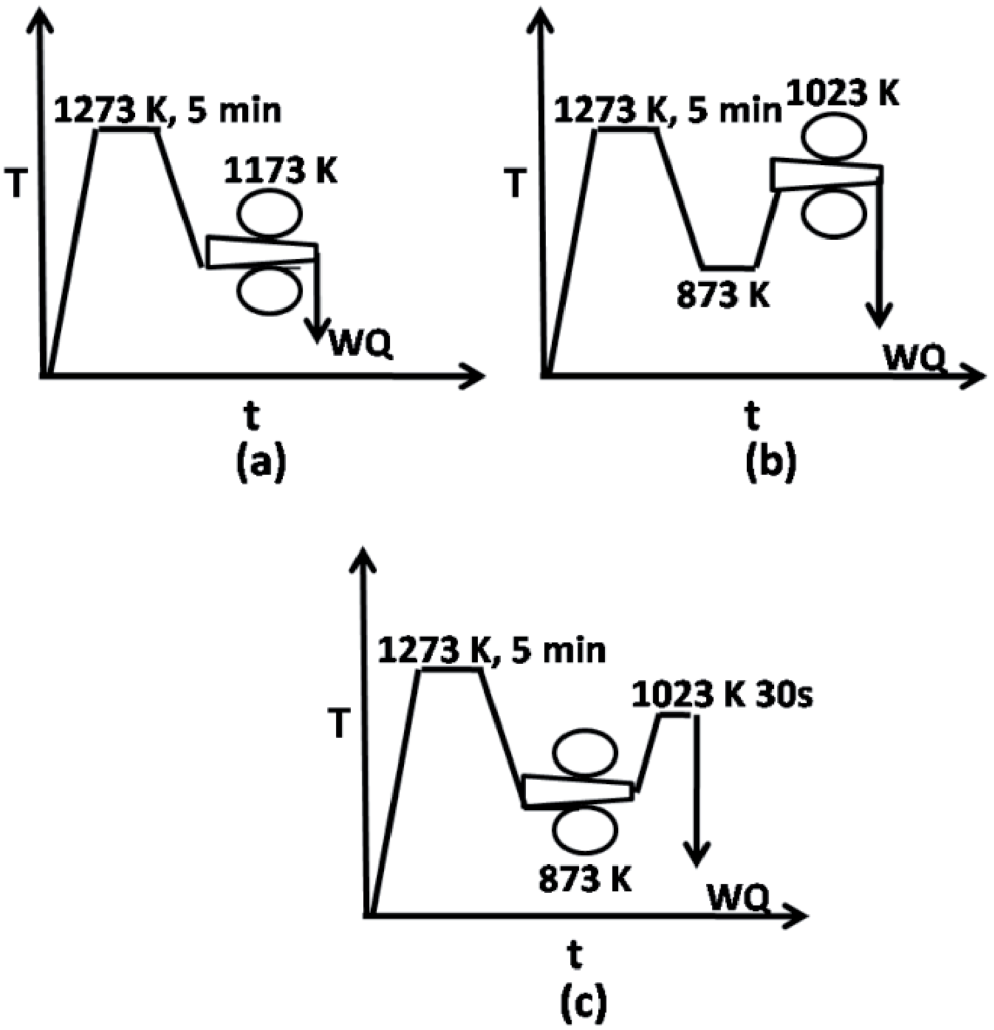

Figure 3.
Various heat treatment processes owing to different ways of thermomechanical treatments in steel.

martensite structures, and on further annealing the aimed ultrafined-grained microstructure was achieved. The achieved strength (UTS) is ~1600 MPa with 30% elongation [13].

The temperature of deformation also plays a vital role in influencing the refinement of the microstructure through hot deformation. In **Figure 3a** the martensitic phase is dominated, resulting in ultrafined grains due to dynamic recrystallization

(DRX) of ferrite grains. In the processing of steel as shown in **Figure 3b**, the martensitic content is above 30% which contributes to the strength of the steel by the varying the degree of deformation. As compared to the routes of **Figure 3a** and **b** with **Figure 3c**, the DRX is not necessary for the formation of ultrafined grains; the warm temperature deformation followed by intercritical annealing can also result in the formation of similar structure. Therefore, the warm rolling and high rate of intercritical annealing and high rate of cooling significantly affect the microstructural properties of the steel.

There are various strengthening mechanisms affecting the strength of the steel. By following specific thermomechanical treatment, the occurrence of twins enhances the strength of the steel. Twinning-induced plasticity steels are FCC crystal-structured steels. The appearance of the crystallographic twins greatly depends on the stacking fault energy (SFE), and the SFE of the steel is controlled by the rate of heating treatment. Temperature is directly proportional to SFE. Low SFE (below 20 mJ/m^2) results in the conversion of austenite to martensite (i.e., TRIP effect), whereas high SFE (above 20 mJ/m^2) gives TWIP effect (formation of twins). The dislocation generated during the deformation is obstructed by the twins and, therefore, increases the strength of the steel [32, 33].

Thus by adopting this technique, the microstructural modification takes place by the combined effect of mechanical and thermal energy. There are also iterative thermomechanical processes where percent of deformation is applied prior to heat treatment (**Table 1**). This process also contributes to the resistance of corrosion with respect to the orientation of the grain [3, 14, 21, 23].

The above heat treatments are aimed to enhance the specific properties of the high-alloyed steel to get rid of unwanted properties. Some of the microstructures evolved during processing are given in **Figure 4**.

The behavior of steel in exterior load describes its mechanical properties. Plastic deformations are supported by the movement of dislocation and the presence of twins, and precipitates hinder the motion of dislocations and thereby increase the strength of the steel. Mechanical properties are associated with the yield stress, separating the elastic and plastic regions, where the activity of dislocation extends [15–17, 30–32]. Pinning of dislocations by random obstruction is controlled by the misfit and size of the particles. In general, larger SFE promotes dislocation gliding, which enables the dislocation to move freely. On the other hand, the smaller SFE increases the area between the two partials, thereby making the motion of dislocation difficult and resulting in the piling up of dislocation. For the duration of the dislocation union, the partials must reconnect to prevail over the obstruction

Steel type	Maximum forging temperature (°C)	Burning temperature (°C)
Carbon steel	1200	1349
Nickel steel	1249	1380
Chromium steel	1200	1370
Nickel-chromium steel	1249	1370
Stainless steel	1280	1380
TWIP steel	1200	1350
High-speed steel	1280	1400

Table 1.
Various steels corresponding to different ranges of deformation temperature.

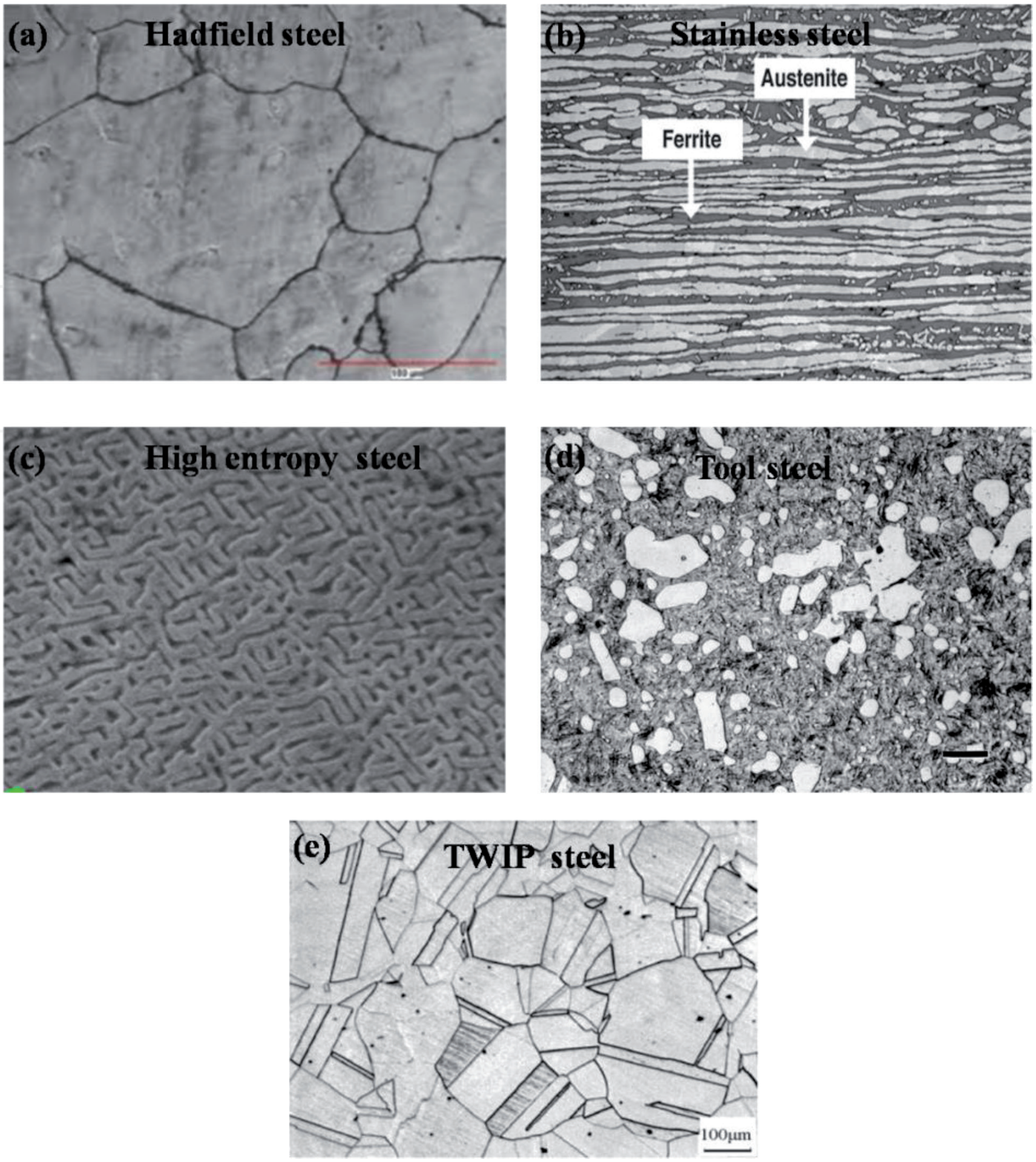

Figure 4.
Various microstructures of high-alloy steels.

[30–34]. The opposition of steel to plastic deformation reduces with rising SFE, and for this reason the SFE should be lowered to reinforce the strength. Based on the observation, SFE is regulated by alloyed elements in the steel for preferred enhanced properties like strength, hardness, or rate of work hardening.

6. Application of high-alloy steel

High-alloy steels have vast applications such as:

- Stainless steel: it has excellent corrosion properties and is used in structural applications, refrigerator, freezers, food packaging, etc.

- Tool steel: used in dies, shear blade, rollers, cutting tools, etc.

- TWIP steel: used in automobiles, ship building, infrastructure, railways, aircrafts, etc.

- High-entropy steel: used as structural material in low-temperature applications due to its high toughness.

- Hadfield steel: used in railways, structural applications, shafts, gears, housing, cables, etc.

- High-speed steel: used as cutting tool materials due to its high hardness like drilling machine, blades, etc.

7. Conclusions

High-alloyed steels are complex alloys, along with desired chemical composition and multiple phased microstructures through various heat treatment processes. Various strengthening mechanisms through controlled heat treatment techniques are adopted to achieve excellent mechanical properties. The chapter examines the advanced methods used in the field of heat treatment routes for high-alloyed steel and focuses on their structure-property relation. The high-alloy steels acquire its enhanced mechanical properties from the modified microstructures of austenite, ferrite, martensite, and some carbides. Ferrite and austenite provide the formability, whereas martensite provides strength to the steel in addition to the low-temperature transforming phases like bainite and retained austenite to achieve better combinations of mechanical properties. The advanced thermomechanical treatments used for high-alloy steels aim to explore the possible phases that contribute to the mechanical properties. In thermomechanical routes aims on heat treatment as the microstructural qualities required for the steels are mainly achieved by post-deformation controlled heat treatment processes. From the above discussions, it can be concluded that the microstructure and its properties are based on variation in chemical composition and processing conditions. Determined by latest demands for the performance of the high-alloy steel in various applications, the progress of thermomechanical processing is introduced.

8. Futuristic development of high-alloy steel

High-alloy steel has undergone significant evolution through time. Around 70% is used in various applications. These steels are highly demanding as they display various environmental, chemical, physical, and mechanical properties. Here the different proportions of alloying element in steel provide various mechanical properties. As can be seen from the foregoing, high-alloy steel plays an important role in the building and construction industries as well as in automotive industries. High-alloy steel offers economy, high performance, corrosion resistance, high strength, durability, lightweight and high performance under extreme conditions, and its wide variety of products for desirable applications.

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