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# High-Carbon Steel in Additive Manufacturing

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# High Carbon Steel in Additive Manufacturing

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## I. Introduction

The first known use of carbon steel dates back to 500 A.D. when a blacksmith mistakenly used iron ore as a primary material for smithing. This material, as the name suggests, is made up of both carbon and iron. Carbon steel, as one of the most abundant at the time, was used most frequently in European and Asian countries. Carbon steel first appeared around the year 500 AD in Damascus steel swords as well as Japanese swords. They were prized for their sharp edges and sturdiness compared to other weapons of the era. The composition of these swords was very similar to modern carbon steel, yet superior in several mysterious ways (Forged Components 2022).

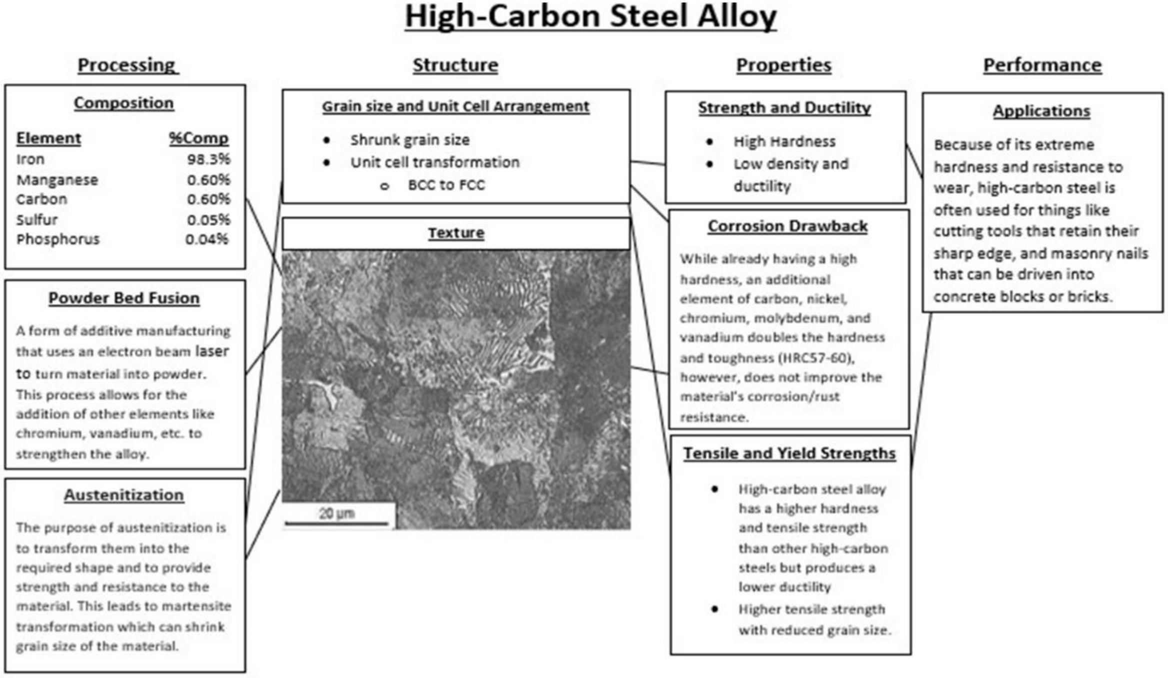
Carbon steels are classified into four categories based on the iron/carbon ratio. Low-carbon steels consist of less than .30%, medium-carbon steels consist of carbon from a range of .30% - .60%, while high and ultra-high-carbon steels have a carbon content of .6% or 1.50% respectively. Generally, carbon is the most important commercial steel alloy. Increasing carbon content increases hardness and strength and improves hardenability. But carbon also increases brittleness and reduces weldability because of its tendency to form martensite (Capudean 2003). This paper will discuss the process, structure, properties and performance of high-carbon steels within additive manufacturing.

## II. Abstract

High-carbon steel is a form of iron alloy that has a high ratio of carbon. This mixture of different components has created a high-tensile, high-strength material that is commonly used in commercial manufacturing. High-carbon steels can be used in a multitude of ways including in car frames, knives, masonry tools, etc. Properties of high-carbon steel like high hardness, high toughness, and wear resistance make it a highly sought-after material.

High-carbon steel can be processed through numerous methods. The method that will be focused on primarily is processing high-carbon steel through means of additive manufacturing. Additive manufacturing is the industrial production name for 3D printing, a computer-controlled process that creates three-dimensional objects by depositing materials, usually in layers. AM methods like wire laser additive manufacturing (WLAM) and electron beam melting (EBM) are all common methods for fabricating high carbon steel. The perks associated with these methods are that they improve some drawbacks of the natural properties of high-carbon steel. This paper discusses the uses of these additive manufacturing methods along with other methods used in the processing of high-carbon steel, how properties (i.e., microstructure, grain size, etc.) are affected, and the capabilities of the material.

**PSPP Map**



**High-Carbon Steel Alloy**

**Processing**

**Composition**

| Element | %Comp |
|---|---|
| Iron | 98.3% |
| Manganese | 0.60% |
| Carbon | 0.60% |
| Sulfur | 0.05% |
| Phosphorus | 0.04% |

**Powder Bed Fusion**

A form of additive manufacturing that uses an electron beam laser to turn material into powder. This process allows for the addition of other elements like chromium, vanadium, etc. to strengthen the alloy.

**Austenitization**

The purpose of austenitization is to transform them into the required shape and to provide strength and resistance to the material. This leads to martensite transformation which can shrink grain size of the material.

**Structure**

**Grain size and Unit Cell Arrangement**

- Shrunk grain size
- Unit cell transformation
    - BCC to FCC

**Texture**

**Properties**

**Strength and Ductility**

- High Hardness
- Low density and ductility

**Corrosion Drawback**

While already having a high hardness, an additional element of carbon, nickel, chromium, molybdenum, and vanadium doubles the hardness and toughness (HRC57-60), however, does not improve the material's corrosion/rust resistance.

**Tensile and Yield Strengths**

- High-carbon steel alloy has a higher hardness and tensile strength than other high-carbon steels but produces a lower ductility
- Higher tensile strength with reduced grain size.

**Performance**

**Applications**

Because of its extreme hardness and resistance to wear, high-carbon steel is often used for things like cutting tools that retain their sharp edge, and masonry nails that can be driven into concrete blocks or bricks.

## III. Destructive Distillation of Coal

High-carbon steel alloy can also be created through numerous processes. One way of making it is by using virgin steel or recycled steel parts. As the name suggests, when scraps cut off from components made of steel are extracted, they then get smelted down into steel blocks which are used to craft other items made from recycled steel. On the other hand, virgin steel is created by heating iron ore and coke (coal heated in a vacuum/airless chamber). This process is known as the destructive distillation of coal (DDC).

Pyrolysis or destructive distillation is an irreversible chemical change caused by the action of heat in the absence of oxygen (in the presence of oxygen the name of the process is combustion). Without oxygen, the energy input splits the chemical bonds and leaves the energy stored (Vergara and Pimental 1978). This would require the coal to temperatures between 400 – 450 °C. However, only a fraction of the material is retained from this heating process while the other portion is converted into either ash, non-volatile tar, or char (**Figure 1**). Using extreme heat(s) to burn coal only increases the carbon content of the coal. This is primarily because the carbon content in coal is proportional to temperature.

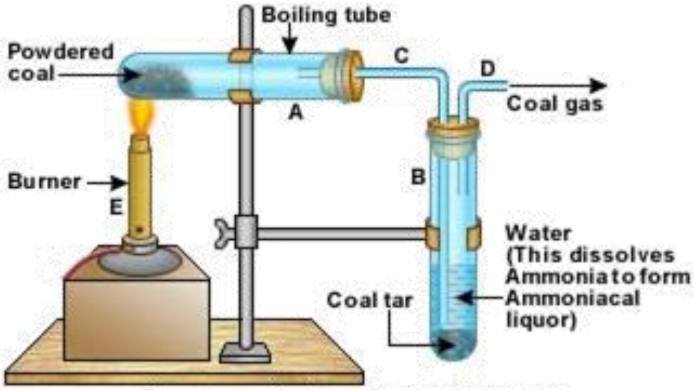


***Figure 1: Destructive Distillation of Coal Process***

The use of DDC is but a method used to create coal with carbon content higher than normal. This method can prove useful in prematurely filling the masses of coal with carbon to increase the intake while heating the iron. An alternative method would be to use a mass amount of coal on the metal to make it intake the carbon produced by coal, trapping the carbon into the iron forming high-carbon steel.

## IV. Process

High carbon steel alloy contains 1.03 percent recent carbon and small amounts of chromium, molybdenum, and vanadium. After heat treatment, it can reach the hardness of HRC57-60, with very good toughness, but no corrosion resistance (Otai 2020). This is very impressive for material as toughness and hardness are inversely proportional. As one increases, the other decreases in turn. The material properties that govern both hardness and toughness are in essence “counteracting” one another. It’s a give and take for a material (EngineeringExcel 2022). This alloy goes through a commercial treatment process due to it being a common working material. The material is annealed at 899°C then placed in a cooling furnace. This cooling process helps homogenize the composition of the iron and other added elements. This alloy is then forged in 955 to 1177°C heat. It is then put through a hot (94 to 483°C) and cold working process which is needed more for high-carbon steels due to it needing more force to form. It will finally go through a heat treatment process in which the steel is heated in an 899°C furnace and quenched in oil repeatedly and tempered at 372 to 705°C until it produces material of Rockwell C Hardness 55 (AZO 2012).

### Electron Powder Bed Fusion

High-carbon steel alloys can also be manufactured through additive manufacturing (AM). The alloy undergoes a process known as powder bed fusion (PBF) to prepare it for the AM process. Powder bed fusion is an additive manufacturing method which is used during the fabrication process. The purpose of PBF is to consolidate material in powder form to form three-dimensional (3D) objects (Leary 2020). The steel will be exposed to extreme heat by using electron beam melting (EBM) (**Figure 3**). This method produces a stream of electrons that is guided by a magnetic field, melting layer upon layer of powdered metal to create an object matching the precise specifications defined by a CAD model (Markforged 2022). The alloy is then processed at a temperature of 850 °C and prepared for heat treatment. Heat treatment is performed with two purposes: to ease the machining process needed to obtain the mechanical testing specimens and to optimize the as-built material microstructure after the EBM process (Koerner and Markl 2021). Before the alloy is machined, it is annealed at 750 °C heat to improve hardness and retain austenite levels. This process is known as austenitization. The purpose of austenitization is to transform them into the required shape and to provide strength and resistance to the material (Corrosionpedia 2018). The alloy then goes through hot isostatic pressing. This process compresses the alloy using high temperatures (1160 °C), improving the ductility thethe by eliminating processing defects.

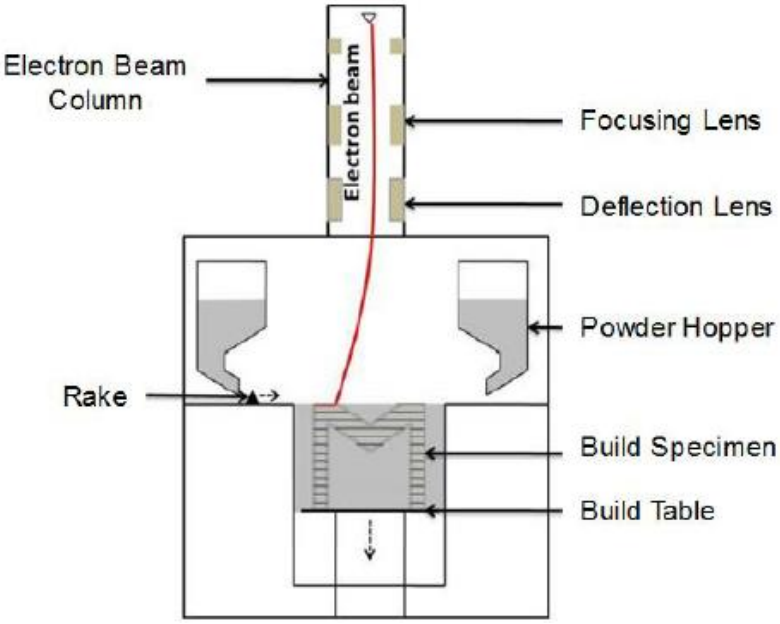


**Figure 3: Additive Manufacturing— Powder Bed Fusion (PBF) method**

### Wire Feed Additive Manufacturing

Wire feed additive manufacturing or wire laser additive manufacturing (WLAM) is a form of laser-based additive manufacturing method. WLAM is commonly used to cast complex structures with materials with smaller grain sizes. The WLAM process being with a laser which superheats metal wire fed through a movable metal deposition. The metal deposition head, which is suitable for 3D printing, is moved over a building platform while it adds the metal powder or the wire by heating it with the laser beam and melting it on the surface (Laserline 2022). Once the initial material is shaped and cooled, an additional layer of superheated wire is placed on top of it forming a three-dimensional component. The strength of the laser beam has a significant impact on the properties of the material. Laser shock processing (LSP) can improve fatigue life, corrosion, wear resistance, and other mechanical properties of metals and alloys (Yi et al., 2015).

## V. Structure and Properties

Structure, or also known as the arrangement of internal components of the material, determines virtually everything about a material. This includes the properties of the material, its potential applications, and its performance within those applications [8]. AS previously stated, carbon steel is the term coined for any steel with carbon content ranging from 0.05 to 2.1%. Pushing the percentage of this content above 2% will cause the material to become very brittle. Generally, high carbon steels contain from 0.60 to 1.00% C with manganese contents ranging from 0.30 to 0.90%. High carbon steels are used for spring materials and high-strength wires. Ultrahigh carbon steels are experimental alloys containing approximately 1.25 to 2.0% C. These steels are thermo-mechanically processed to produce microstructures that consist of fine, equiaxed grains of ferrite and a uniform distribution of fine, spherical, discontinuous proeutectoid carbide particles. Such microstructures in these steels have led to superplastic behavior and correlates to high hardness and lower ductility [1].

High-carbon steels have a pearlite microstructure (**Figure 4**). Pearlite or “pearlite steel” refers to an iron-based composite state. This structure is optimal due to its high toughness, deformability, and strength.

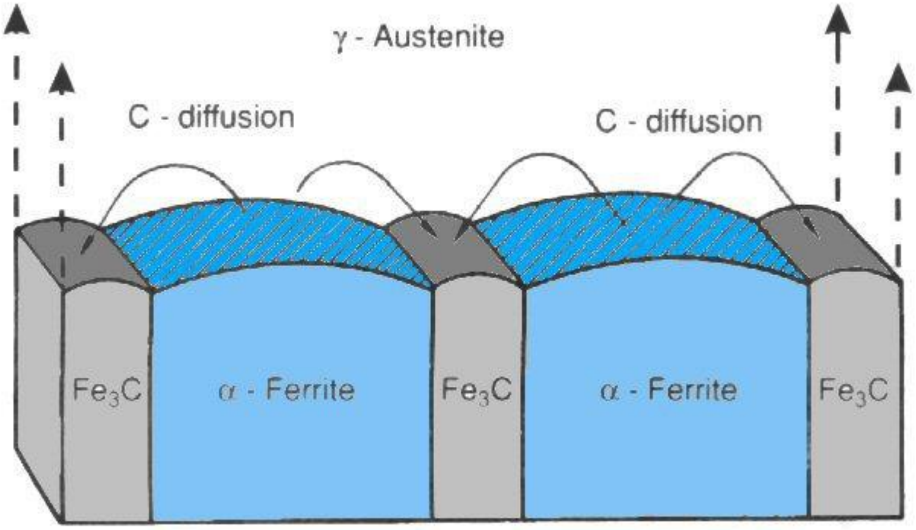


**Figure 4: Pearlite Composition**

Pearlite, a microstructure commonly seen in many grades of steels, is a two-phased, layered structure composed of alternating ferrite (87.5 wt%) and cementite (12.5 wt%) which is present in some steels and cast irons. In the phase of slow cooling of an iron-carbon alloy, pearlite forms by a eutectoid reaction as austenite cools below 723 C, the eutectoid temperature. The Eutectoid reaction involves a single solid phase decomposing into two different solid phases: $\gamma \rightarrow \alpha + \beta$. The iron-carbon system shows this type of reaction [11].

High-carbon steel alloy has a higher hardness and tensile strength than other high-carbon steels but produces a lower ductility. It has a body-cubic (BCC) martensite structure. The martensite structure exhibits high strength but is prone to dislocations and line defects due to the tetragonal crystal structure from interstitial carbon atoms (Gensamer et al., 2012). Line defects weakens the structure along a one-dimensional space, and the defects type and density affects the mechanical properties of the solids. It is made mainly of iron with a composition of 1.03% C, .05% S, .04% P, .5% Mn. While already having a high hardness, an additional element of carbon, nickel, chromium, molybdenum, and vanadium doubles the hardness and toughness (HRC57-60), however, does not improve the material's corrosion/rust resistance. "1095 high carbon steel's carbon content: 0.95%-1.03%.

## Martensite Transformation

High carbon steel alloy can undergo a structural change known as martensite transformation. The martensitic transformation is a diffusion less first order phase transformation in the solid state, which proceeds by the nucleation and growth of the new phase (Ahlers 2004). This is in part due to the composition of the alloy being primarily iron. The iron in the alloy can also go through an allotropic phase transformation, changing from α to β to ϒ to δ phases upon heating. At 790 °C iron transforms from α to β, keeping the same BCC structure. Upon reaching 910 °C, iron transforms into ϒ iron in which the unit cell briefly becomes an FCC arrangement with atoms at the corner and face-center of the cube (**Figure 5**). At 1400 °C, the alloy reverts to a BCC arrangement.

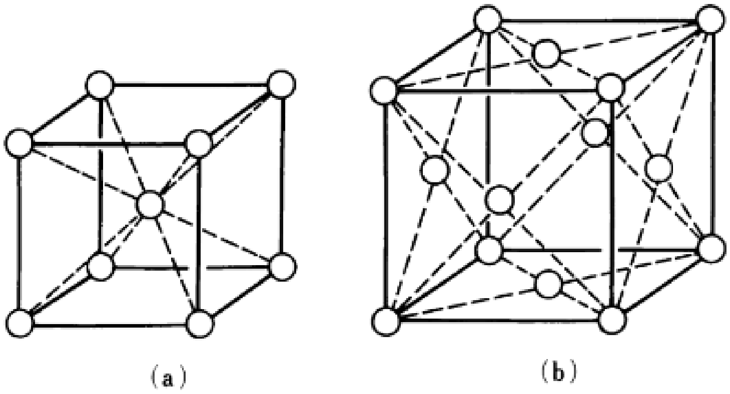


**Figure 5: (a) α BCC Unit Cell Arrangement. (b) ϒ FCC Unit Cell Arrangement**

In addition to the change in unit cell arrangement, the carbon solubility changes within this process as well (**Figure 5**). As shown in the figure, the carbon solubility once the arrangement (α) is at BCC is small, at .03%. Once it transforms into an FCC unit cell rises to 1.7%. This is due to the martensite transformation. During this process the material is being quenched, rapidly cooled to a lower temperature. The martensite transformation depends on this, which can also be seen in figure 5, as the temperature cools the carbon content rises. The crystal structure of martensite obtained by quenching the ϒ phase in carbon steels has a body-centered tetragonal (BCT) lattice which may be regarded as α lattice with one of the cubic axes elongated (Nishiyama 2016). At this stage, in the high-carbon steels, the crystals take the form of bamboo leaves called the midrib. This plane, with respect to the crystal lattice of the parent phase, becomes nearly parallel to the {225} or {259} ϒ plane.

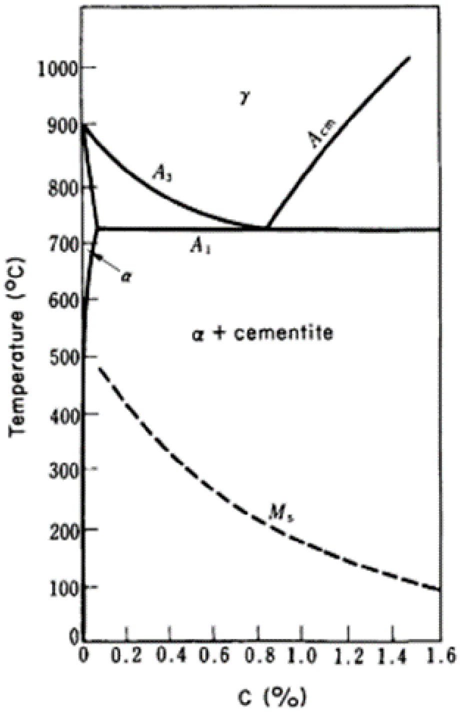


**Figure 5: Phase diagram of Fe-C system**

Martensite transformation can also have an impact on the grain size of the material. In martensite steel, it has been reported that smaller prior austenite grain can lead to smaller martensite packets, which can significantly enhance both strength and toughness (Sun et al. 2018). The martensite substructure of the material is changed from twinning to dislocation due to the grain size shrinking drastically. The average grain size for carbon steel is between 11.5 and 46.3 µm. Larger grain sizes of 47.6 and 70.0 µm are ordinarily a result of being fully annealed. when the austenite grains are refined to about 4 µm, and a simple model based on dislocation slip stress (τ) and twin shear stress (Tτ) has been proposed to illustrate the grain refinement effect on martensite substructure transformation (Sun et al. 2018).

## VII. Performance

In previous discussions, it has been displayed how a higher strain rate prompted plastic twisting to deliver refined grains of metals and make them exceptionally impressive. At the point when intensely disfigured through compressive stacking, metal examples produced a rising thickness of imperfections or separations that really reinforces the metal against additional deformity. Another nanoscale system includes reinforcing by nano twinning. Such exploration is fundamental for controlling the microstructures of high carbon prepared under outrageous activity conditions and, thus, for opening new modern applications for these somewhat low alloyed minimal expense steel.

The average tensile and yield strength of a piece of carbon steel can fluctuate hugely contingent upon the steel's carbon content and other assembling factors. AISI 1020 steel, a low-carbon gentle steel, has a yield strength of 47,900 psi and an elasticity of 65,300 psi.

High-carbon steel is steel that contains between 0.6 percent and 2 percent carbon.
It is extremely hard and is often used for tools, cookware, and knife blades. However, its hardness can make it more brittle than some other steels, and it's difficult to weld and machine (Polycase, 2022). It has been established in prior discussions how a larger strain rate enabled plastic twisting to deliver polished steel grains and make them exceedingly impressive. When metal is extensively stretched by compression stacking, metal samples are then formed creating a growing layer of defects which effectively fortifies the metal against additional deformation. The nanoscale system uses nano twinning for reinforcement which is identified as the in-grain boundaries as a shifted segment of a crystal in which the crystal lattices on each edge are linked across imaginary twin plane by mirror symmetry (Science direct, 2020). To regulate the microstructures of high carbon, steel was produced under high activity conditions and, as a result, to develop new modern applications for these comparatively low alloyed low-cost steel, fundamental research is crucial. Even though high-carbon steel is a very tough metal. It is far steadier than any hardened steel. Furthermore, it is less malleable than treated steel, and even dampness can cause rustiness. To better understand how High Carbon Steel (HCS) responds to cyclic stacking at varied ambient temperatures, bending fatigue experiments are conducted. It shows how the damping, flexible modulus, and recurrence change for different working temperatures ranging from 23°C to 135°C. The effects of the damping are related to the rate of damage accumulation and break growth, both of which are shown to accelerate with rising ambient temperature. Due to the alleged fragility influence, instances are found to generally become weaker with increasing external temperature, and their fatigue life shortens. A finite element model (FEM) is developed to examine the most extreme stress in order to gain a deeper understanding.

Instrumental carbon prepares to have a carbon content greater than 0.8 percent. The name is a hint; given their extreme hardness, these preparations mangadom once porers shearing sharp edges, various types of springs, and every possible type of cutting carried out, blades, and razors. In contrast to treated steel, the iron in carbon steel is susceptible to oxidation (commonly referred to as rust) regardless of its carbon content. Regardless, the higher the carbon content of steel, the safer it is to consume due to its greater general strength.

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## VI. Discussion and Conclusion

We have introduced a metal that is diverse and can be applied in many different ways. This material, as the name recommends, is comprised of both carbon and iron. Carbon steel is one of the most abundant and dependable metals of its time. As previously stated, carbon steel is the term coined for any steel with carbon content ranging from 0.05 to 2.1%. Pushing the percentage of this content above 2% will cause the material to become very brittle. Generally, high carbon steels contain from 0.60 to 1.00% C with manganese contents ranging from 0.30 to 0.90%. High-carbon steels are used for spring materials and high-strength wires. Ultrahigh carbon steels are experimental alloys containing approximately 1.25 to 2.0% C. These combinations of different elements create a bond that allows us to create materials to use in our everyday life without even noticing.

High carbon steel has many purposes because of its remarkable mix of solidarity, toughness, adaptability, and corrosion resistance. From construction projects to vehicle parts to clinical hardware and even your daily household items, this adaptable material is turning into a fundamental part of present-day producing processes across different industries. High-carbon steel is very dependable and will always be used. Although, when exposed to moisture High carbon steel can easily become rusted from corrosion. It does not have a major effect on it immediately, but it can eventually affect the strength of the material. Corrosion can also be removed from high-carbon steel and re-strengthen. These are facts that prove why high-carbon steel is so dependable and able to be used in many different aspects of life.

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