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Review Article

A Comparative Review of Annealing Processes for Eutectoid Steel: Microstructural Evolution and Mechanical Property Development

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Abstract *- Eutectoid steel is widely used in structural and tooling applications. Its performance strongly depends on the microstructural changes produced during annealing. Although full, process, and spheroidizing annealing are known techniques, their efficiency and limitations are not systematically compared in the existing literature. This review examines these processes with respect to carbide morphology, pearlite transformation, and mechanical property development. Full, process and spheroidization annealing treatments increase ductility and reduce hardness. In contrast, in conventional annealing, the process is slow and energy-intensive, and non-uniform carbide microstructures are also observed. These are some of the major barriers to high-volume production of these materials in industries. The recent developments in these materials are also reviewed in this paper. Examples include rapid isothermal annealing, cyclic heat treatment, annealing furnace strategies, and microalloying strategies; machine-learning-assisted process control is also used. These techniques ensure higher stability of carbides, reduce the time for treatment, and improve machinability. The present review presents a clear comparison of annealing routes, identifies the gaps between industry and science, and provides guidelines toward future improvement. It points out a roadmap toward faster, energy-efficient, and application-specific annealing strategies for eutectoid steel.*

Keywords *- Annealing, Eutectoid Steel, Mechanical Properties, Microstructure, Annealing Routes.*

1. Introduction

Eutectoid steel can be defined as a special type of alloyed steel that consists of a unique composition allowing it to undergo eutectoid transformation upon cooling. There are many reasons why eutectoid steel is an important group of steel, one of which is the versatile application of eutectoid steel in various industrial processes. This versatility allows eutectoid steel to be applied in tools and machines due to its strength, hardness and ductility. These properties are directly connected to the formation of microstructure after annealing (Bhadeshia, 2012). Annealing is an important process allowing for the strategic modification of the internal lattice of eutectoid steel in a process of temperature regulation and proper cooling. Annealing leads to the removal of structural defects, redistribution of alloying elements, and grain refinement. All things depend on the annealing temperature and soaking time.

Eutectoid steel is widely used in bearings, tools, automotive parts, wire goods, and precision engineering due to its excellent properties, such as strength, hardness, wear resistance, and fatigue characteristics. All of these properties are highly dependent on the annealing process since it determines pearlite formation, carbide formation, grain formation, and mechanical behavior. There are many heat treatments that can be performed; however, the most common ones are full annealing, process annealing, and spheroidizing annealing due to their widespread use in industries. It becomes very difficult to select the most suitable annealing process since each heat treatment has its own microstructural characteristics, processing parameters, and properties such as hardness, ductility, machinability, and toughness.

While many experimental studies have described the effect of individual annealing treatments on eutectoid steel, there is a lack of coherent literature on the subject. The reason is that existing publications usually address a certain type of annealing treatment or some particular processing parameter, thus precluding comparison of various annealing treatments. Reviews on this subject usually emphasize the metallurgical part of a specific technique. Nevertheless, there is no comparative study of such essential aspects as process variables, microstructural and mechanical properties formation. Moreover, industrial applicability and energy

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efficiency of this process are rarely considered. Finally, the most up-to-date techniques of annealing, such as cyclic annealing and furnace atmosphere improvement, are often not reviewed thoroughly enough.

In order to bridge this gap, this paper attempts to perform a critical comparison of full annealing, process annealing, and spheroidizing annealing through recently published literature. Through this review, the relationship between annealing conditions and the microstructure, carbide morphology, mechanical properties, and application of different annealing methods has been established by discussing existing limitations, new technologies, and future prospects of the field. Through the synthesis of information obtained from various studies in a single comparative study, this paper hopes to provide practical insights to choose effective annealing strategies.

While various aspects of annealing processes have been explored, certain key gaps still persist in the existing literature. All these pending questions and issues substantially restrain scientific understanding and industrial implementation of optimized heat-treatment strategies. The main research gaps that exist include:

- Lack of comprehensive comparative analyses linking microstructural evolution with changes in mechanical properties across full annealing, process annealing, and spheroidizing annealing.
- Insufficient explanation is provided on how microalloying elements Mn, Si, Nb, and Mo influence the kinetics of annealing, the refinement of pearlite, and spheroidization behavior.
- Limited research on data-driven and machine-learning-based predictive models for real-time optimization of the annealing parameters.

Very few industry-sponsored studies have tied furnace atmosphere control, annealing cycle duration, and energy efficiency to carbide morphology and end-material performance.

Objectives of the study are given below:

- To compare different types of annealing techniques for eutectoid steel.
- To discuss the microstructure mechanism involved and the transformation.
- To discuss the mechanical performance.
- To identify the industrial uses and constraints using the literature-based solution.

1.1. Nature of Eutectoid Steel

Eutectoid steel consists of iron and carbon; normally, the carbon content lies in the range of 0.75 to 0.85%. Therefore, it occupies an important position in metallurgy. Accordingly, the eutectoid transformation involves the conversion of austenite simultaneously into ferrite and cementite. Among the elements present in eutectoid steel, carbon has the most profound effect on the mechanical properties of the steel. The mechanical properties of eutectoid steel can be controlled in such a way that it meets the product development criteria by altering the amount of carbon present in the steel, along with the size and shape of the microstructural constituents. Thus, further R&D is necessary in this area.

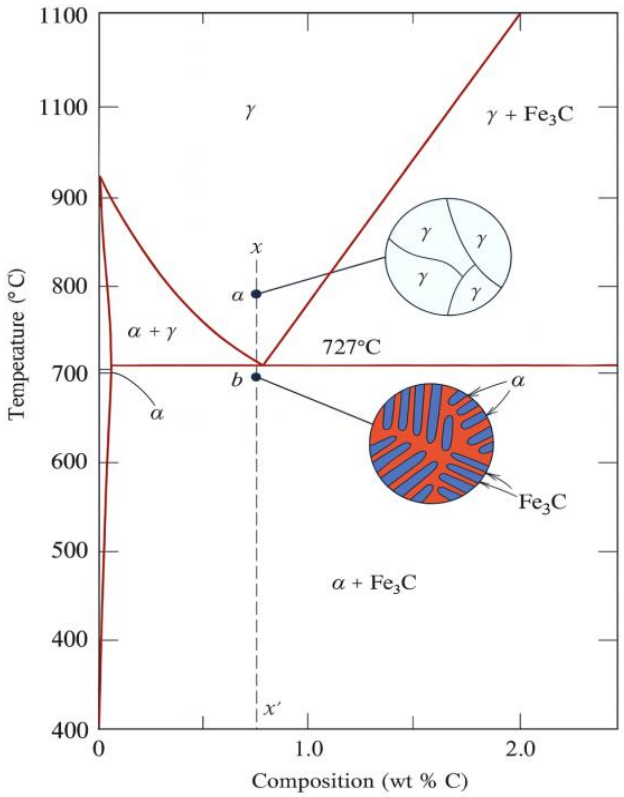


Fig. 1 Microstructure of Eutectoid Composition Representation in Iron-Carbon Diagram Below and Above at Eutectoid Temperature (Callister & Rethwisch, 2017)

Fig. 1 displays the microstructure of an iron-carbon alloy that consists of 0.8 wt% Carbon, referred to as an eutectoid alloy (Inthidech & Matsubara, 2019). From the figure, temperature is represented on the y-axis while carbon content is displayed on the x-axis. The figure demonstrates the transformation of austenite to pearlite through the process of slow cooling of steel below the eutectoid point at 727°C. Pearlite comprises ferrite and cementite in a layered form. Steel that has been heated beyond 727°C consists of one single phase, which is the austenite.

In the case of austenite, carbon is dissolved in the face-centered cubic iron crystal structure. On reduction of temperature below the critical point, austenite gets converted into pearlite by a phase transformation process (Mensching et al., 2020). Thus, it leads to better mechanical properties like strength and ductility. In order to achieve the desired mechanical properties for the product design, such as higher

hardness and ductility, the mechanical properties of the lamellar pearlite can be altered. This involves the size, shape, and distribution of the lamellae. The above topic also remains a subject of research since the type of pearlite structure before annealing affects the efficiency of the annealing process.

1.2. Chemical Composition of Eutectoid Steel and Its Effect on Annealing Process

Table 1. Chemical Composition wt% of Eutectoid Steel as Per IS 2507

% C	% Mn	% S	% P	% Si
0.75 – 0.85	0.50 – 0.80	0.050	0.050	0.10 – 0.35

Besides carbon, the chemical composition of eutectoid steel can include special alloying elements like manganese, silicon, etc. In that way, the alloy will be granted further features and obtain structural refinement, which will improve its performance (Baday et al., 2016; Pricop et al., 2016). Generally, Eutectoid Steel contains a chemical composition as shown in Table 1.

The microstructure of eutectoid steel and its mechanical properties depend on this specific composition. This is why the description of annealing methods for eutectoid steel starts from the discussion of its chemical composition and some basic features that form the starting point for further analysis. The carbon content in eutectoid steel is 0.75-0.85 wt.%, with the various Mn, Si, and Cr contents. The differences in the chemical composition have an influence on the process of annealing. Higher C content of 0.75-0.85 wt.% leads to an increase in volume fraction of cementite, reduction in spheroidization kinetics, and the residual hardness after annealing (Sun et al., 2025). Mn content influences the annealing process by decreasing the dissolution rate of carbides and increasing hardenability during the annealing process.

Increased content of Mn improves the hardenability and slows down the dissolution of carbides during the annealing process. Si content affects the process by limiting the coarsening of cementite and facilitating pearlite refinement (Skowronek et al., 2025). Cr additions contribute to stabilization of the carbides and have an impact on their spheroidization kinetics and morphology (Skowronek et al., 2025; Porter & Easterling, 2009; Bhadeshia, 2021). These factors should be taken into consideration when analyzing several papers because even small changes in the composition affect the diffusion process and pearlite refinement.

1.3. Overview of Initial Microstructure of Pearlite

Microstructural complexities largely affect the mechanical and thermal properties of eutectoid steel. The lamellar structure of pearlite consists of interleaving layers of ferrite and cementite (Rastegari et al., 2015). Fig. 2 shows the microstructure of Pearlite. The Light Phase is (α) ferrite, and the thin layer is cementite (Fe3C). It shows the microstructure of pearlite, which has a distinctive lamellar arrangement. These alternating ferrite and cementite layers create the classic pearlitic pattern.

They illustrate the two-phase mixture formed during the eutectoid transformation in steel. This microstructure helps explain the mechanical properties of pearlite, such as its good balance of strength and ductility (Bhadeshia, 2021).



Fig. 2 Microstructure of Pearlite (Light Phase is Ferrite and Thin Layer is Cementite) (Callister & Rethwisch, 2017)

Cementite in the pearlitic microstructure typically provides a hardness of about 220–300 HV in the pearlitic condition, depending on colony size, lamellar spacing, and cooling rate. The lamellar arrangement increases its resistance to deformation, hence making this material suitable for those applications that require robust mechanical properties. Ferrite present in the microstructure imparts ductility and toughness, and cementite imparts hardness in the material.

The proper balance is required for such applications where the material needs to take mechanical stress and impacts, without causing brittle failure. The pearlite structure is finely interwoven and influenced by the cooling rate in its solidification, a factor that influences the machinability of eutectoid steel.

This comes into application where precision and ease of machining are necessary. It is extensively used in structural components, automotive parts, cutting tools, and precision machinery due to its balanced strength, hardness, and ductility (Bhadeshia, 2021).

Interlamellar spacing is significant in the determination of the mechanical properties and the efficiency of the final annealing treatment carried out on the eutectoid steel. As the research and development activities carried out on the annealing treatment of eutectoid steel progressed, it was observed that different pearlite microstructures behave differently when they undergo the annealing treatment. As the cooling process is carried out on the eutectoid steel, two types of pearlite microstructures are generally observed to be formed in the steel. Rapid cooling generally results in the formation of fine pearlite, whereas slow and controlled cooling results in the formation of coarse pearlite (Onwudili & Iweka, 2021). The microstructure that is first developed during the cooling process has a significant effect on the efficiency of the final annealing treatment carried out on the steel; hence, research is essential in this direction. The effects of these changes on the annealing treatment carried out on the steel are explained in the annealing section.

2. Literature Review from Previous Studies

Although individual annealing techniques or general transformations in eutectoid steel are addressed in many studies and reviews, most studies have addressed each process separately, and none have presented a systematic comparison of full, process, and spheroidizing annealing techniques.

Although most reviews on this topic are addressed in the previous reviews, most reviews are based on traditional mechanisms or empirical studies, and none have systematically integrated findings from multiple studies or resolved the differences in microstructural development, pearlite transformation, or carbide formation, as presented in the literature. Also, the most recent advances in energy efficiency, or data optimization, are not addressed in the previous reviews. Table 2 is presented to show an overview of recent studies on annealing techniques and their results.

Table 2. Overview of Recent Research on Annealing Techniques and Associated Outcomes

Reference	Annealing Type	Key Research Summary
Skowronek et al., 2025	Full Annealing	Full annealing causes an improvement in the mechanical properties and stability of the microstructure of medium-Mn steels, with high sensitivity of the mechanical properties to precise time-temperature control.
Onwudili & Iweka, 2021	Full Annealing	Annealing at 1000°C causes an improvement in ductility but a reduction in hardness, with slow cooling resulting in a refinement of the grain size, thus improving toughness and reducing brittleness.
Sun et al., 2025	Process Annealing	Process annealing causes an improvement in magnetic properties due to a reduction in internal stresses and the generation of nanocrystals without phase transformation.
Nasiri & Mirzadeh, 2019	Spheroidizing Annealing	Spheroidization leads to an alteration in lamellar pearlite to spherical carbides, which causes softening because of the reduction in hardness and improvement in ductility and machinability.
Adedayo et al., 2010	Spheroidizing Annealing	Accelerated spheroidization leads to a refinement in carbide distribution, which causes an improvement in the hardness-toughness index of GCr15 bearing steel.
Alcántara, 2021	Full annealing / Process Annealing	Continuous annealing with temperature control leads to improved uniformity of mechanical properties, increasing the production of high-quality steel and decreasing reworking.
Amos et al., 2018	Full Annealing/ Spheroidizing Annealing	Optimized annealing conditions promote carbide spheroidization, decrease hardness, and improves steel formability.
Bharti et al., 2020	Full Annealing	Accurate full annealing conditions lead to significant improvements in the strength, hardness, and toughness of AISI 4140 steel.
Caruso & Godet, 2010 ;	Process Annealing	Process annealing improves additively manufactured maraging steel by decreasing stresses and precipitation hardening.
Cheng et al., 2015	Spheroidizing Annealing	Spheroidizing-critical annealing: The process improves surface hardness and core toughness of carburized steel without affecting machinability.

2.1. Novelty and Contribution of the Present Review

A number of review papers have been reported on individual annealing processes or certain heat treatment processes for steels. All of the previously published reviews mainly concentrate on one type of annealing process, like full annealing, process annealing, or spheroidizing annealing, but do not provide a comparative study on their processing parameters, microstructure, mechanical property development, industrial application, and latest technology advancements. The role of furnace atmosphere, previous deformation, microalloying additions, energy conservation, and intelligent process control strategies is yet to be reviewed comprehensively.

This review is different from other studies since a comparative review of three annealing processes in eutectoid

steel has been carried out. This study is different from other review papers since a correlation between the parameters of the annealing process and carbide shape, pearlite transformation, grain structure development, mechanical properties, and application is done based on the recent literature review. In addition, the recent advancements like hydrogen annealing atmosphere, rapid and cyclic annealing techniques, machine learning for process optimization, and energy-efficient furnace technologies have been reviewed.

The second vital aspect of this study is that the scientific challenges and industrial issues found in the literature are addressed. The research gaps in the current studies are outlined along with the possibilities of future research in areas like microstructural characterization, predictive modeling of processes, sustainable heat treatments, and intelligent furnace control. Thus, this review, while being a summary of current knowledge, also provides a framework for selecting an appropriate annealing process along with future possibilities of research.

3. Types of Annealing Processes

Annealing is one of the heat treatment processes where metals are heated up and then slowly cooled down to a specified temperature. Annealing reduces the internal stresses, improves ductility and other mechanical properties of the metal. The structure of the metal changes during annealing, and hence it becomes softer and workable. In general, this process is applied not only to steel, but also to other metals in order to put them through further processing or to make them more efficient.

Table 3. Comparison between annealing process (Skowronek et al., 2025; Bharti et al., 2020; Sun et al., 2025; Cheng et al., 2015)

Annealing Process	Process Description	Annealing Temperature in °C	Microstructural Change	Author's Note	Future Research Scope.
Full Annealing.	At the critical temperature, heat the steel and hold for some time (as per the properties requirement), then slow cooling in a furnace.	Between 790°C and 845 °C.	It converts fine pearlite to coarse pearlite.	This process is effective for achieving maximum softness and ductility, but the cycles increase production time.	Investigate optimized cooling rates and minimize cycle time. Investigate alternative atmospheric conditions to enhance grain refinement.
Process Annealing.	At a lower temperature, heating the steel for a short time period and furnace cooling.	Between 650°C and 713 °C.	It converts fine pearlite to coarse pearlite.	This process is quick and economical and suitable for improving formability in cold-worked steels.	Research on eco-friendly gas atmospheres and their effect on mechanical properties and surface finish.
Spheroidizing Annealing.	Mostly at temperatures below the eutectoid point, the steel is heated and held for a long time period and then furnace cooling.	Between 700°C to 750°C	It converts pearlite to spheroidite.	This process is critical for enhancing the tool life and reducing brittleness in high-carbon steel.	Develop a composition of novel alloy and a heat treatment cycle to optimize carbide morphology for a specific application.

3.1. Full Annealing

Based on multiple literature reviews to improve the efficiency of the full annealing cycle for eutectoid steel, it involves heating the steel to a temperature above the critical range A1 (temperature 50°C above A1), but doing so uniformly. The temperature varies between 790°C and 845°C for eutectoid steel (Feng & Yang, 2007). At this temperature or within this range, the steel would undergo transformation into austenite. This is a phase that has an FCC crystal structure. In some instances, this temperature might be different depending on the actual composition of steel alloy. When this temperature has been attained, the steel should be held at this temperature for a time sufficient to allow for the uniform distribution of heat throughout the material. It generally ranges from 30 minutes to several hours to ensure uniform temperature distribution and complete transformation. It depends on the material thickness. After the soaking time has passed, steel is cooled slowly - usually within the furnace (Furnace cooling at 28 °C/h) (Durgaprasad et al., 2017). Such slow cooling is required in order to reduce internal stresses and equalize the microstructure of steel. The mentioned method ensures a uniform structure in eutectoid steel for improving its mechanical properties and characteristics. Fig. 3 shows the Full annealing - binary iron-carbon phase diagram for Steel.

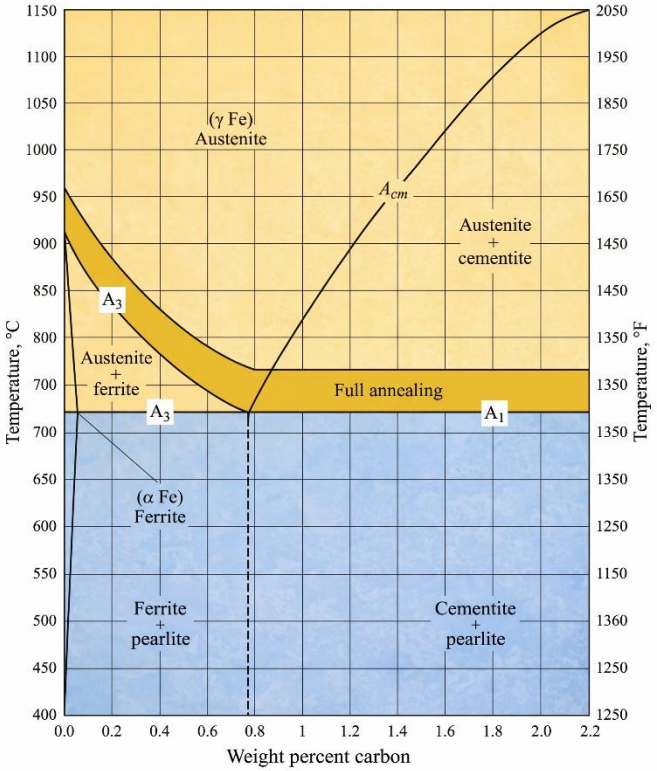


Fig. 3 Binary Iron Carbon Phase Diagram for Steel - Full Annealing (Durgaprasad et al., 2017)

3.2. Process Annealing

Based on the literature, to improve the efficiency of process annealing for steel, eutectoid steel shall be heated to a temperature between 10°C and 20°C above the A1 temperature. The temperature range is between 650°C and 713°C (Gazder et al., 2011; Gorkunov et al., 2017). This temperature range is below that of full annealing but high enough to achieve the desired effect of eliminating stresses. The objective shall be to relieve internal stresses and to induce limited microstructural changes without significant coarse-graining. The temperature usually ranges between 600°C and 700°C (Humphreys & Hatherly, 2004; Huang et al., 2022). The process is retained for a shorter period compared with that in full annealing. It is usually between 1 and 3 hours, depending on the specific material and desired properties. In the cooling stage of process annealing of eutectoid steel, the material is cooled in air or by any other controlled method after the holding period. The rate of cooling may vary, but it is usually moderate. Fig. 4 shows the process annealing - binary iron-carbon phase diagram for Steel.

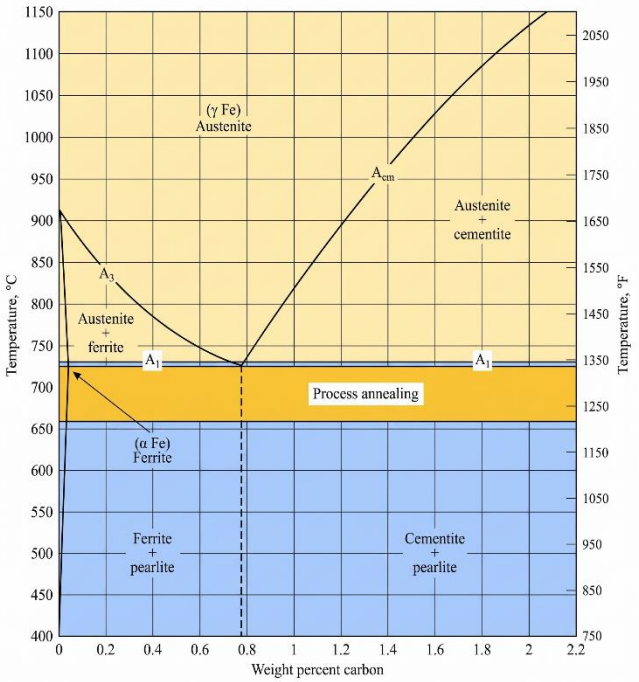


Fig. 4 Binary Iron Carbon Phase Diagram for Steel - Process Annealing (Durgaprasad et al., 2017)

In the case where process annealing is used, as the authors' observation and analysis, the temperature of the Steel is made lower than the eutectoid point, and as a result, the steel does not experience any changes in its microstructure due to the absence of the austenitic transformation. Instead, there is recovery and recrystallization in the microstructure. This process is conducted in order to restore the ductility and relieve the stresses that have developed in the steel. It is recommended that during this process, select coarse pearlite as the raw material, and slow cooling takes place. It is recommended that a cooling rate of 10-20°C per minute is adequate in order to maintain the structural stability. These things improve the efficiency of the process.

3.3. Spheroidizing Annealing

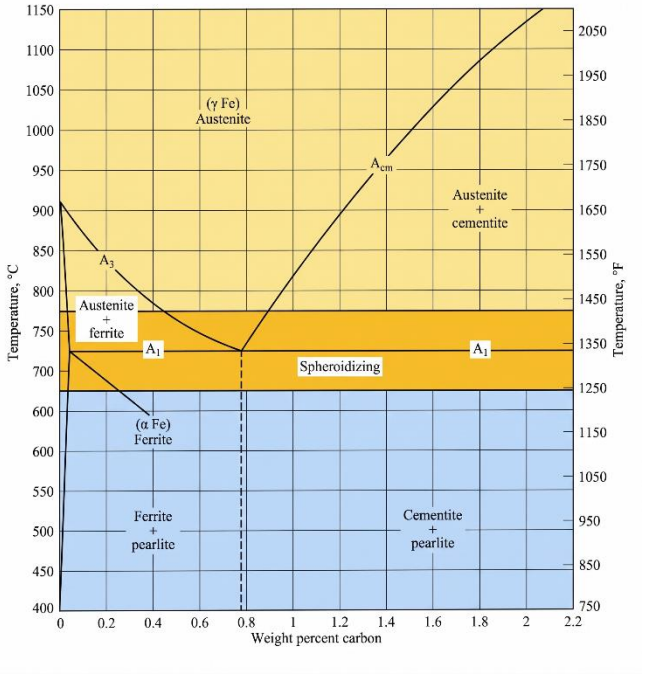


Fig. 5 Binary Iron Carbon Phase Diagram for Steel - Spheroidizing Annealing (Durgaprasad et al., 2017)

Based on the literature, to improve the efficiency of spheroidizing annealing for steel, eutectoid steel is heated up to a temperature below its eutectoid point, within the range from 700°C to 750°C. The choice of a particular temperature in the range shall depend on composition and desired microstructural objectives. The eutectoid steel is held at this temperature for a number of hours and, in some cases, for as long as 20 - 48 hours.

The steel is subsequently cooled very slowly after the holding period, and this normally is within the furnace (Furnace cooling at 15 °C/h) (Jagnade et al., 2025). The cooling has to be slow to avoid further creation of stresses in the material and loss of refinement in the microstructure achieved during holding. During the process, carbide particles can take a spherical form. It allows better ductility, reduction of hardness, and improvement in machinability (Karadeniz, 2008; Lü et al., 2016). Fig. 5 shows the Spheroidizing annealing - binary Iron carbon phase diagram for Steel.

From the analysis and observations presented by the authors, the microstructure of the steel has an effect on spheroidization annealing of eutectoid steel. In this case, the metal is heated to a temperature close to the eutectoid temperature but lower than the eutectoid temperature. This means that there is no formation of the austenite structure in the process. A fine pearlitic microstructure is therefore recommended as the best initial microstructure for this type of heat treatment. The interlamellar spacing is reduced in the fine pearlite, and this makes the cementite plates break down to form spheroidal particles. The carbon diffusion distance in the cementite lamellae is shorter due to closer spacing, which makes carbides unite and form globules. It is also recommended that cooling in a furnace at 650°C be used during the process.

3.4. Advanced and Hybrid Annealing Processes

Some of the most recent advances in heat treatment processes are characterized by the development of methods that will allow for decreasing processing time, increasing energy efficiency and obtaining a fine microstructure that cannot always be obtained using classical annealing techniques – full, process or spheroidizing annealing. Therefore, many advanced and hybrid annealing methods have been developed for the processing of eutectoid and high-carbon steels.

3.4.1. Rapid Thermal Annealing

Rapid Thermal Annealing (RTA) is the heat treatment process that involves heating the steel at extremely high rates of more than 50-100°C/min and subsequent controlled short-time holding and cooling. As compared with classical annealing in furnaces, RTA substantially decreases the overall time of the process and prevents the formation of excessive grain growth. Due to the shortness of the process, fine pearlite colonies are obtained during RTA and carbide spheroidization can be accelerated by applying prior cold working. Such methods are especially promising in the case of the use of such processes on continuous lines due to their productivity and low energy consumption.

3.4.2. Laser Annealing

Laser annealing is a process that uses a localized heat treatment method where the laser beam delivers rapid surface heating while having minimal effect on the temperature of the material around the workpiece. It allows for controlled heat application, controlled heating rate and controlled heating area, thus making it possible to selectively soften wear-resistant or high-carbon steel parts. For eutectoid steel, laser annealing may be used for improving pearlitic structure, reducing stress concentration Moreover, increasing the surface formability of the part without the need for overall heating of the part in the furnace.

3.4.3. Cyclic and Intercritical Annealing

In cyclic annealing, heating and cooling occur at temperatures close to the range of eutectoid transformation, specifically below the subcritical and intercritical range. This helps in breaking down the lamellae of cementite and facilitates its transformation into spheroidized carbide. In intercritical annealing carried out between A1 and A3 temperatures, structures of ferrite and austenite are formed, which could further transform to pearlitic or spheroidized structures depending upon the cooling rate. This process has received considerable attention owing to its potential to significantly reduce the time for spheroidizing annealing.

3.4.4. Hybrid Thermomechanical/annealing Process Techniques

A hybrid process technique involves deformation followed by an annealing process. In the case of cold rolling, warm working, or severe plastic deformation, a large number of dislocations and subgrain boundaries are created that act as nucleation sites for recovery, recrystallization and spheroidization of the carbides during the annealing process. Such processes may offer an advantage of improved kinetics of spheroidization, carbide homogeneity, and energy savings when compared to normal furnace annealing.

3.4.5. Comparative Evaluation

The modern methods of annealing that have been described above can be used alongside traditional annealing approaches without replacing them completely. Full annealing is still the best method to use in order to achieve maximum structural homogenization, process annealing is useful in recovering ductility in cold-worked materials, and spheroidizing annealing works well in providing better machinability through spheroidizing of carbides. On the other hand, there are many benefits of using rapid, laser, cyclic, and hybrid annealing technologies.

4. Effect of Full Annealing, Process Annealing and Spheroidizing Annealing on material mechanical properties

Figures 6 and 7 show a comparative analysis of the impact of full annealing, process annealing, and spheroidizing annealing on the mechanical properties of eutectoid steel. From the radar chart, there is an indication that there is a normalized comparative analysis of the various processing and mechanical parameters of eutectoid steel. These parameters include annealing temperature, holding time, hardness, elongation, impact energy, and machinability. The parameters of eutectoid steel are shown in the bar charts. These parameters include the variation in major mechanical properties of eutectoid steel after undergoing various annealing processes compared to the initial state of eutectoid steel without undergoing any form of annealing treatment. The various figures are created by the authors after review and analysis of various important research papers to indicate a clear comparative analysis of the effect of various annealing processes on the strength, ductility, toughness, and machinability of eutectoid steel.

The results obtained in the comparative analysis illustrate the impact of full annealing on the mechanical properties of eutectoid steel. The hardness value decreases from 250 HV in the initial state to close to 175 HV in the treated state. This shows that there is a decrease in the hardness of the steel. However, there is an increase in elongation from 7.5% to 21.5%, while impact energy also shows an increase from 15 J to 35 J. This shows that there is an improvement in ductility (Sun et al., 2025; Skowronek et al., 2025). Machinability index also shows an increase from 0 to 20%. The change in the mechanical properties of eutectoid steel during full annealing may be attributed to the fact that full annealing relieves the steel of internal stresses. This means that steel can be uniform in its microstructure. Thus, it is less brittle and can deform without breaking.

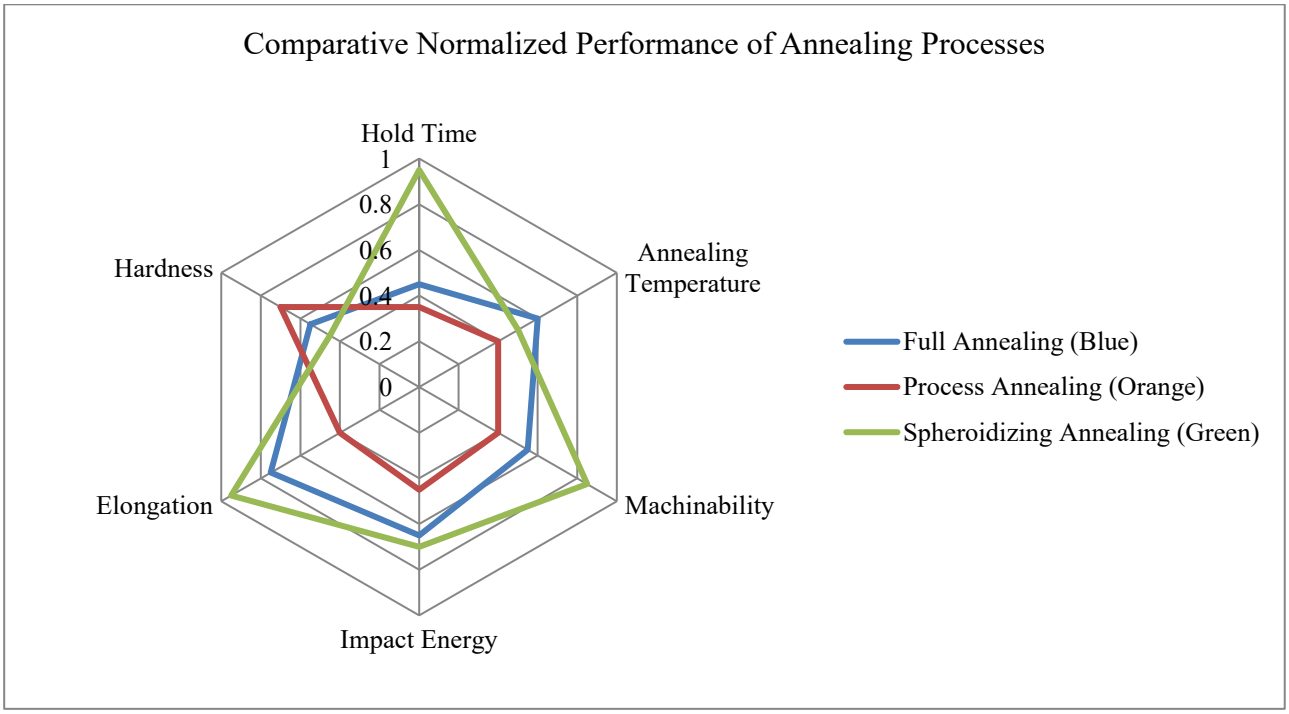


Fig. 6 Radial Chart– Based Comparison of Annealing Processes from Different Literature Sources

The comparison data also reveal the impact of process annealing on eutectoid steel in relation to the balancing of its strength and ductility. Here, there is a moderate loss in hardness, from 250 HV in the initial state to around 200 HV. This means that there is a process of softening, but this is still at a relatively high level compared to the full annealing state. In contrast, there is a rise in elongation from 7.5% to 11% and the impact energy rises from 15 J to 26.5 J (Alcántara, 2021). This indicates that there is a rise in ductility and toughness, but not excessively. Machinability index rises slightly to 5%. All this is in line with the nature of process annealing, where there is a relieving of the residual stresses developed in the metal due to the cold working process, and not much change in the structure of grains. The loss in hardness and incremental changes in ductility and Toughness shows that the process of recrystallization is partial and not total. In such a way, there is retention of the original strength of the material while making it resistant to the formation of brittleness.

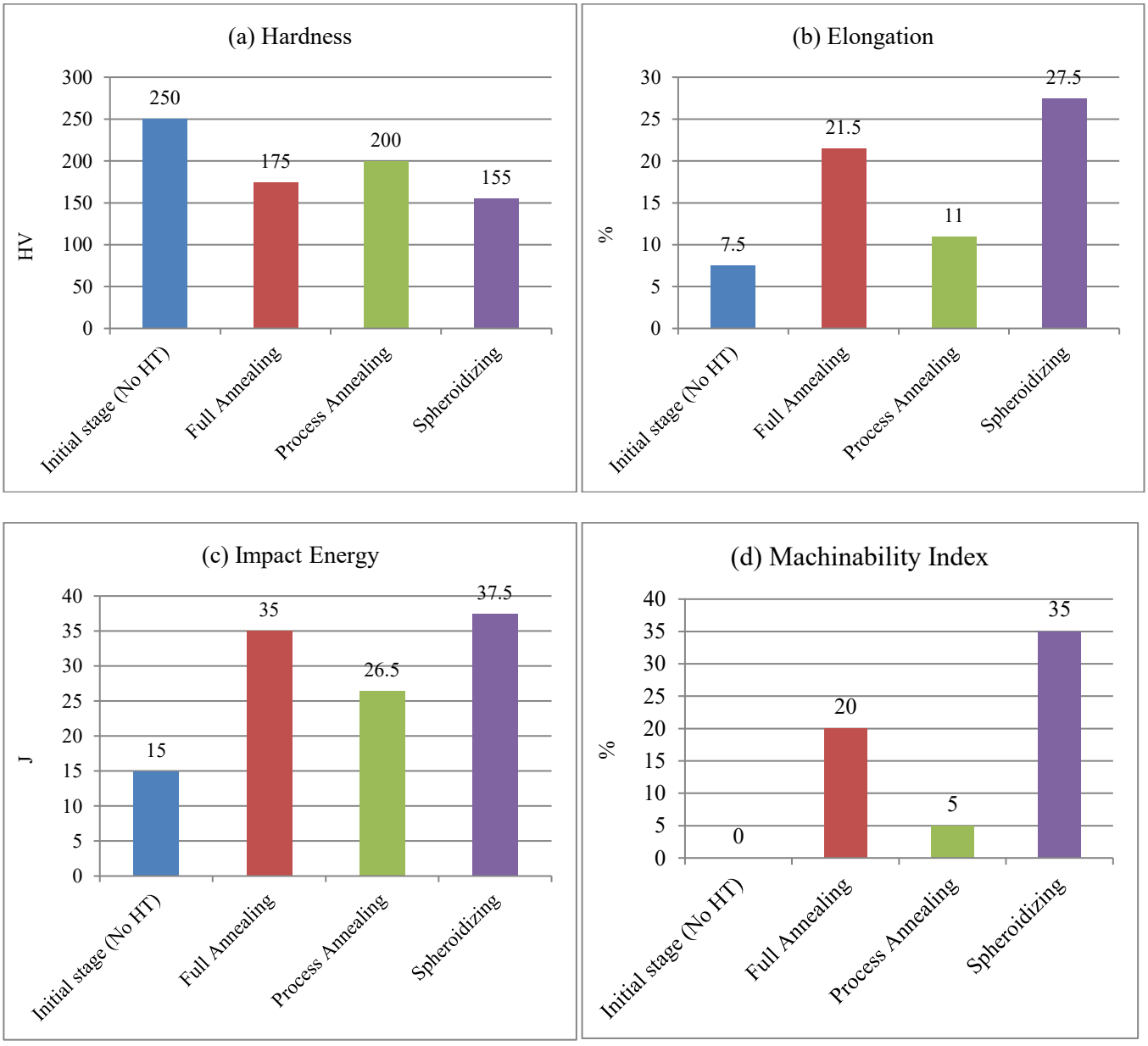


Fig. 7 Mechanical Properties at the Initial Stage and After Different Annealing Processes

The data in the chart clearly shows the impact of spheroidizing annealing on the mechanical properties of eutectoid steel. Under this condition, the hardness value is reduced further to 155 HV, the lowest value among all the conditions. This shows the material has been softened considerably. At the same time, the value of elongation increases significantly to 27.5%, the highest value among all the conditions. Impact energy is also increased to the

maximum value of 37.5 J. The machinability index is increased significantly to nearly 35%. This is because of the formation of spheroid carbide in the ferrite matrix, which reduces the concentration of stress and enables plastic deformation with ease. The reduction in the hardness of the material, coupled with an increase in ductility and toughness, indicates that the material is less brittle, which prevents it from cracking.

The machinability of the material has also been improved, which enables the material to be machined with ease without any wear on the tools (Sun et al., 2025). From the above analysis, it can be concluded that the microstructure of the material is stable and consistent after spheroidizing annealing, thus enabling it to be deformable, tough, and precise in machining.

5. Effect of Full Annealing, Process Annealing and Spheroidizing Annealing on Material Microstructure

The impact of different annealing treatments on the microstructural development in eutectoid steels is shown in Fig. 8. From the graph, the change in the average grain size is shown with respect to the initial state, full annealing, process annealing, and spheroidizing treatments. From the graph, the most notable feature is the increase in the grain size, which is more pronounced in full annealing, and then gradually decreases with process annealing and spheroidizing. Such behavior indicates that microstructural features are highly sensitive to particular treatments. This trend provides a basis for relating grain sizes with associated mechanical properties.

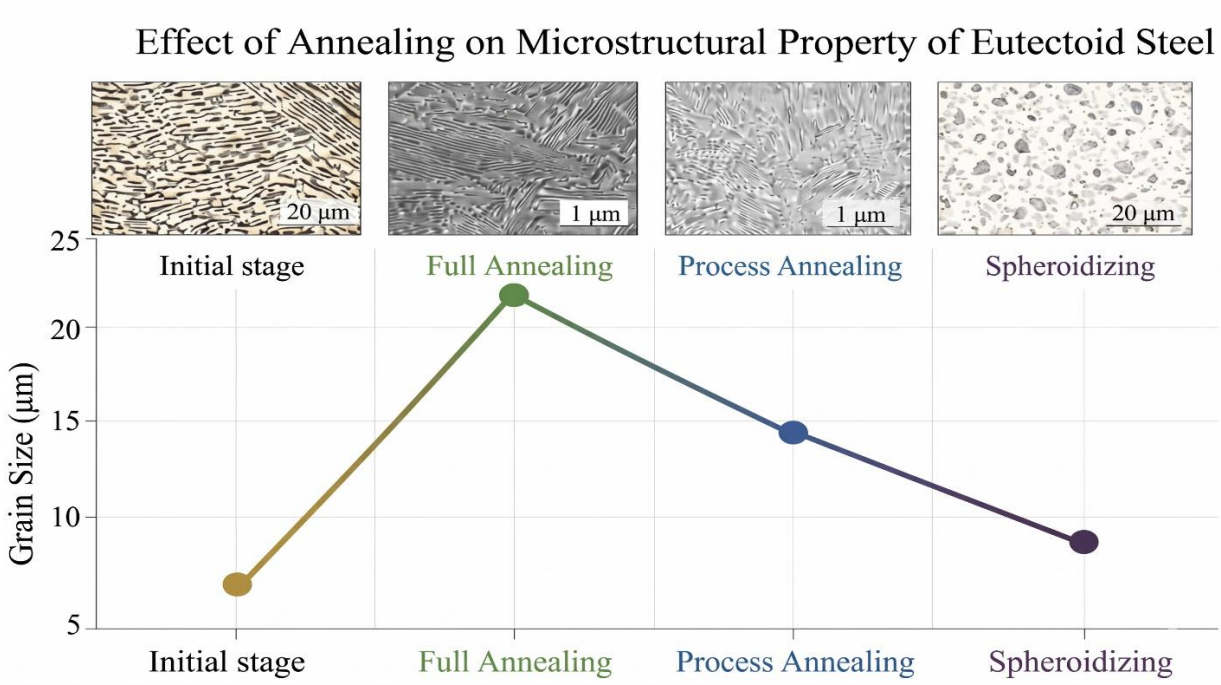
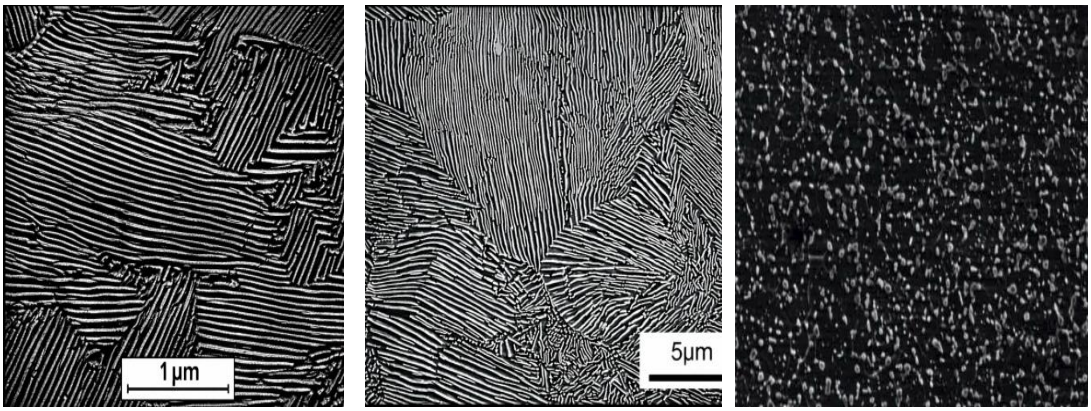


Fig. 8 Effect of Annealing on Microstructural Properties of Eutectoid Steel

Full annealing is associated with the most significant microstructural development, mainly in terms of considerable coarsening of pearlite. The interlamellar spacing of ferrite and cementite is considerably increased, which in turn leads to significant reductions in hardness with corresponding improvements in ductility (Onwudili & Iweka, 2021). Prolonged heat treatment at high temperatures may also allow for partial dissolution of cementite in ferrite, along with considerable grain growth in ferrite. As depicted in Figure 5, this state is associated with the largest grain sizes among all treatments, which is consistent with the associated softening behavior. On the contrary, the microstructural transformation that takes place during process annealing is relatively low. The lamellae of pearlite remain intact without undergoing any coarsening, but there takes place recovery and some recrystallization, which leads to the reduction of dislocations and internal stresses. Consequently, a refined microstructure is obtained, which is evident from the small grain size (Sun et al., 2025). The combination of properties in this state is the most favorable in terms of strength, ductility and machinability. Microstructural transformation in the case of spheroidizing annealing is unique in that the lamellar structure of pearlite is converted into the spheroidized structure consisting of cementite and ferrite matrix. Such a microstructure ensures the maximum reduction of the interfacial energy; therefore, providing the maximum ductility and machinability. It can be clearly observed from Fig. 9 that the microstructure obtained has the finest effective grain size in comparison with other states.



SEM Image of Eutectoid Steel After Full Annealing (Amos et al., 2018) | **SEM Image of Eutectoid Steel After Process Annealing (Huang et al., 2022)** | **SEM Image of Eutectoid Steel After Spheroidizing Annealing (Huang et al., 2022)**

Fig. 9 Microstructure Images of Eutectoid Steel after Annealing Process

5.1. Microstructural Characterization Methods for Annealed Eutectoid Steel

The accurate characterization of microstructure is very important in studying the effects of annealing on transformation characteristics and mechanical behavior of eutectoid steel. The use of complementary methods is usually needed since no one method is capable of describing all the transformations taking place during annealing.

Optical Microscopy (OM): The optical microscope is probably the most popular tool for the preliminary analysis of annealed microstructures. Following proper metallographic preparation and chemical etching, the OM allows one to observe ferrite, pearlite and spheroidized carbide structures, obtaining qualitative data on their evolution and grain structure.

Scanning Electron Microscopy (SEM): SEM has high spatial resolution compared to optical microscopy and finds wide application in studies of carbide structure, interlamellar spacing of pearlite, spheroidizing of cementite, and fracture surfaces. The images obtained by SEM allow for the analysis of cementite particle structure, size, and distribution, and hence make SEM one of the most widely used methods in the research of spheroidizing annealing.

Electron Backscatter Diffraction (EBSD): EBSD is an important tool for crystallographic characterization since it gives the orientation maps of grains, grain boundary distribution, recrystallized fraction, grain size evaluation, texture development, and local misorientation. Therefore, the EBSD technique is very useful for the evaluation of recovery and recrystallization during process annealing.

Transmission Electron Microscopy (TEM): The TEM provides nanometric analysis of the structure of carbides, dislocations, and the interface between ferrite and cementite. TEM is particularly valuable in analyzing the early stages of carbide spheroidization and diffusion-controlled transformation processes that are beyond the capability of traditional optical and SEM microscopy.

X-ray diffraction (XRD): XRD can be utilized for crystal phase identification, determination of the lattice parameters, calculation of the crystal size, and determination of residual stress after annealing. This method will allow the detection of retained phases and add bulk structural information to microscopic data.

Quantitative image analysis: Quantitative analysis of the size, aspect ratio, circularity, volume fraction, and spheroidization of carbides based on optical and SEM images is now possible owing to the availability of modern image analysis software.

Microhardness Mapping: Microhardness testing is often employed in conjunction with metallographic characterization in order to find relationships between microstructural modification and mechanical behavior. The hardness map shows microstructural homogeneity, stress relief, and variation in carbide distribution following different annealing operations.

When used together, these methods provide an overall picture of the effect of annealing on the development of the microstructure. Even though optical microscopy and SEM are the most commonly employed methods due to their ease Moreover, efficiency, more advanced methods such as EBSD, TEM, and XRD can supply additional quantitative data.

6. Application of Full Annealing, Process Annealing and Spheroidizing Annealing in industries

The Fig. 10 illustrates the distribution of annealing processes in different sectors of major industries in the market. From Figure 10, we can also conclude that full annealing is

done in the heavy sector, process annealing is done in the automotive sector, and spheroidizing annealing is done in the precision sector, which includes the tooling and bearing sectors. Figure 10 presents the sector-wise distribution of annealing processes across major industries and is generated by the authors through analysis of multiple resources, published literature, and market reviews.

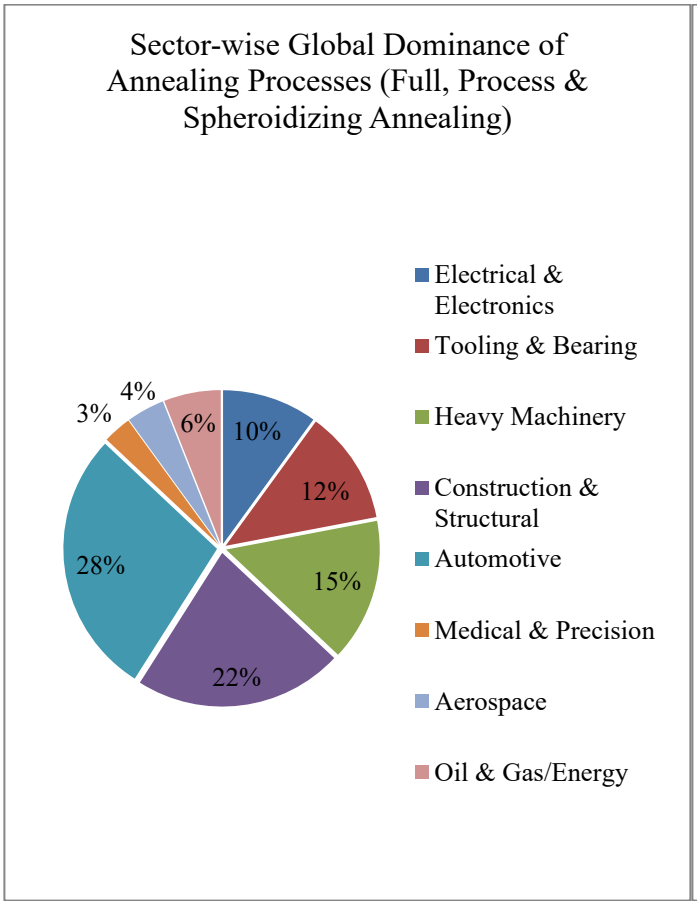
6.1. Application in Industry

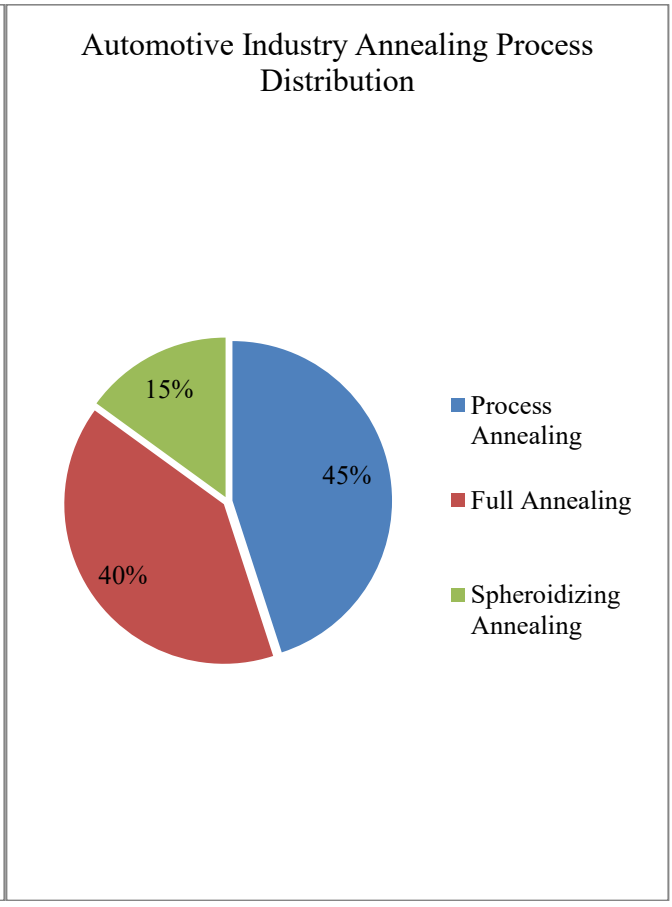
The process of full annealing has wide application in the industrial world, particularly in the automotive industry, accounting for 28% of all the uses of full annealing in industries. It accounts for almost 40% of the total processes that use full annealing. Other industries that widely use full annealing include construction and heavy machinery industries, where up to 65% of the processes use full annealing for making things softer, consistent, and machinable (Onwudili & Iweka, 2021). Process annealing is also important in the mass production process, accounting for 45% in the automotive industry and 25% in the construction and heavy machinery industries, improving ductility and making the process easier and not having to heat up the materials too much (Sun et al., 2025). Spheroidizing annealing is widely used in the precision industries, such as tooling and bearing industries, accounting for 50% of them, making them more machinable and less susceptible to wearout, while in automotive and heavy machinery industries, it is 15% and 10%, respectively.

6.2. Structural Applications

For structural purposes, full annealing is recommended, as it can remove internal stresses, thus making the material homogeneous in all directions. It is used in construction sectors, which cover almost 65% of all annealing operations. Process annealing accounts for 20-25% of operations in construction sectors, as it enhances formability in sheet materials. Spheroidizing annealing, though of limited use in structural components, is of utmost importance in precision components such as bearings, accounting for 10% in heavy machinery operations, though in precision components, the use of spheroidizing annealing can be as high as 50% (Jagnade et al., 2025).

From the above, it can be concluded that full annealing is used for structural purposes, process annealing for efficient production, and spheroidizing annealing for precision machining operations.





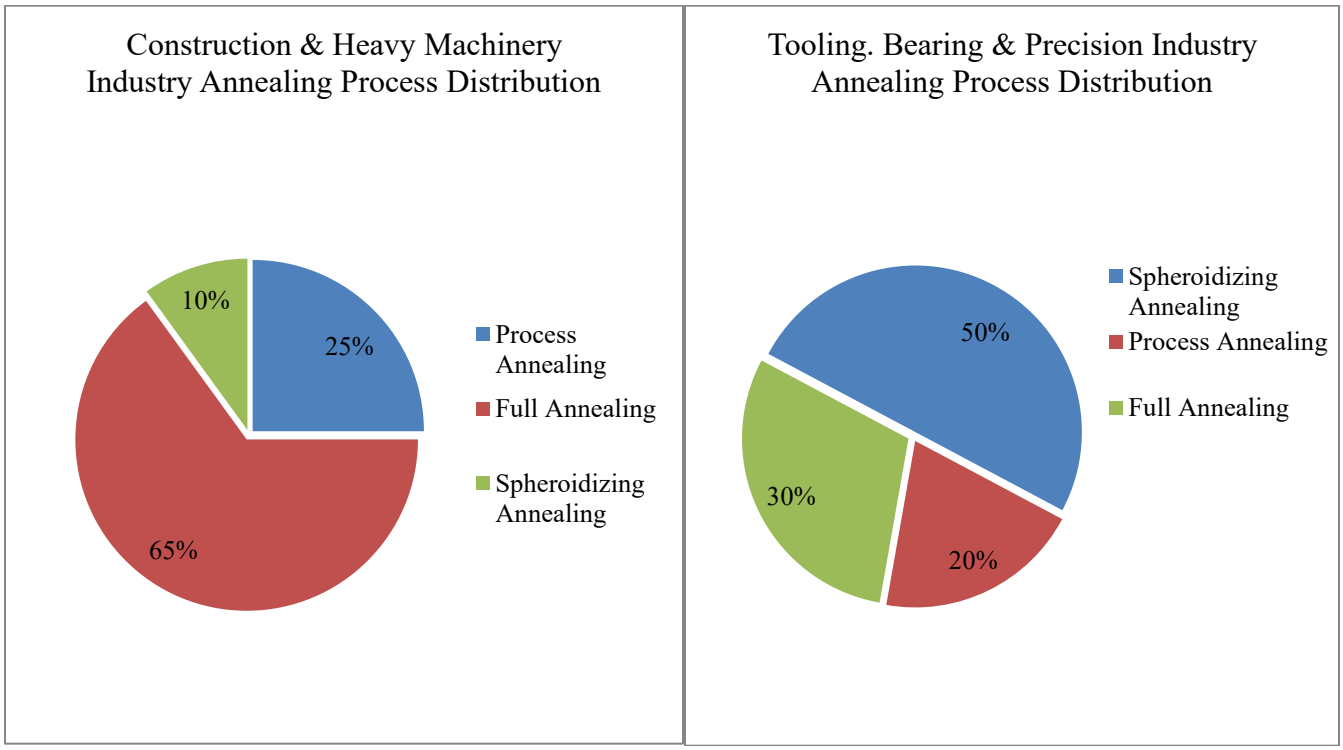


Fig. 10 Pie Chart for Sector-wise Contribution of Different Annealing Processes

Table 4. Research Gaps in Annealing of Eutectoid Steel and Solutions Proposed by the Authors

Ref.	Research Gap	Metallurgical Issue	Proposed Solution	Expected Improvement
Mishra et al., 2017 ; Mudda et al., 2025	Optimization of Annealing Cycles & Energy Efficiency	Traditional full annealing involves slow furnace cooling, leading to coarse pearlite and high energy consumption.	Use rapid isothermal annealing at A1 (Ac1 + 20°C), followed by controlled cooling.	Faster processing, refined pearlite structure, lower energy use, improved machinability.
Mishra et al., 2017; Jagnade et al., 2025	Spheroidization Kinetics & Austenite Decomposition	Long spheroidization time (20–48 hrs) limits industrial efficiency.	Cyclic spheroidization annealing: Alternating between subcritical (~700°C) and intercritical (~740°C) temperatures to accelerate carbide coalescence.	Reduced annealing time, fine spheroidized carbides, better machinability, and improved toughness.
Jagnade et al., 2025	AI-Assisted Annealing for Process Control	Conventional methods lack real-time phase monitoring, leading to variability in properties.	Apply machine learning (ML) models trained on dilatometry data to predict optimal annealing parameters.	More precise heat treatment, optimized grain growth, and controlled carbide precipitation.
O'Brien & Hosford, 1997 ; Páez et al., 2024	Effect of Microalloying Elements	Limited understanding of Mn, Si, and Nb on annealing response and phase transformations.	Study micro alloying effects on carbide stability, pearlite refinement, and diffusion kinetics.	Enhanced mechanical properties, tailored hardness-ductility balance for specific applications.

Table 5. Analysis of suitable annealing process for required mechanical properties for eutectoid steel (Skowronek et al., 2025; Bharti et al., 2020; Sun et al., 2025; Cheng et al., 2015)

Characteristic	Suitable Annealing Process	Data Range	Metallurgical Basis for Eutectoid Steel	Additional Notes
Relief of Internal Stresses	Full Annealing, Process Annealing	Internal stress reduction: ~50–90% (depending on cold work severity)	Stress relief reduces dislocation density and minimizes residual stresses in the pearlitic structure.	Essential for cold-worked eutectoid steel to avoid distortion and cracking during further processing.
Improved Ductility	Full Annealing, Process Annealing, Spheroidizing Annealing	Elongation improvement: ~15–30% (depending on annealing process)	Ductility increases due to refined or softened pearlitic structures and reduced dislocations.	Spheroidizing annealing enhances elongation by promoting carbide spheroidization, allowing greater plastic deformation.
Enhanced Toughness	Full Annealing, Spheroidizing Annealing	Impact energy: ~20–50 J (Charpy test for eutectoid steel)	Homogeneous microstructure increases resistance to crack propagation and improves impact resistance.	Full annealing achieves uniform toughness; spheroidizing reduces brittleness by altering carbide morphology.
Softened Material	Full Annealing, Spheroidizing Annealing	Hardness reduction: ~10–40% (depending on initial condition and annealing process)	Hardness decreases by transforming pearlite into spheroidite or coarse pearlite.	Spheroidization offers the greatest softening, making the material suitable for machining applications.
Improved Machinability	Spheroidizing Annealing	Machinability index improvement: ~20–50% (based on carbide morphology changes)	Spherical carbides reduce tool wear and improve chip formation, enhancing machinability in eutectoid steel.	Ideal for precision machining applications, such as cutting tools and gears, requiring a consistent surface finish.
Reduction in Hardness	Full Annealing, Process Annealing, Spheroidizing Annealing	Vickers hardness reduction: From ~250 HV to ~150–200 HV (depending on process and hold time)	Reduction occurs as fine pearlite transforms into coarse pearlite or spheroidite, reducing material strength.	Spheroidizing annealing results in the lowest hardness values due to carbide rounding.
Grain Refinement	Full Annealing	Grain size (ASTM number): From ~5–6 (as-rolled) to ~8–10 (after full annealing)	Fine pearlite grains are formed during controlled cooling, optimizing ductility and toughness.	Grain refinement in full annealing enhances the toughness-ductility balance for structural applications.
Carbide Morphology Changes	Spheroidizing Annealing	Spheroidite fraction: ~70–90% (depending on duration and temperature)	Lamellar pearlite transforms into spherical carbides, reducing stress concentrators and improving machinability and toughness.	Critical for eutectoid steels used in high-precision machining, offering improved tool life and reduced material brittleness.

7. Summary of Previous Works on Annealing Mechanisms and the Effect of Annealing

In previous works, it is clear that the mechanisms behind annealing have both consensus and considerable differences. In some works, it has been proposed that carbon diffusion during full annealing is controlled mostly by fast migration at the interface of ferrite-cementite, which happens due to a huge interfacial area and leads to significant thinning of lamellae and partial dissolution of carbide (Gazder et al., 2011). In other studies, the focus has been on the predominant influence of pearlite colony boundary diffusion, especially when the content of Mn or Si was higher, resulting in considerably slow dissolution. In most works, lamella fragmentation and curvature-driven coarsening control the rounding of carbides during spheroidization. However, there are contradictions regarding the influence on the speed of this process. According to some researchers, spheroidization occurs quickly due to the creation of a defect network via cold working. In other words, the effect of the atmosphere in the furnace is stressed, such as the ability of hydrogen to reduce the surface energy of carbide. There is an inconsistency

concerning the influence of microalloying elements like Nb or Mo on cementite breakdown (Opara et al., 2025).

From various sources, spheroidizing annealing is better than full annealing because of its ability to give the highest machinability, lowest hardness, and highest dimensional stability. As reported in many sources, the hardness of steel in spheroidizing annealing ranges between 140 and 170 HV. Furthermore, it leads to the formation of round and homogeneous carbide structures. These structures make the machining process easier since the force required to cut the material is reduced by 30 to 50 % (Mishra et al., 2017). On the other hand, full annealing produces coarse pearlite structures, which have a hardness ranging between 150 and 200 HV (Onwudili & Iweka, 2021). Even though this process provides high ductility, it does not provide the high machinability that can be obtained in spheroidizing annealing. Also, in applications where fatigue resistance is necessary, spheroidizing annealing is better than full annealing since it reduces stress concentrations due to the rounded carbide structure compared to the lamellar structure (Mudda et al., 2025). However, for applications that require high ductility and moderate strength in a shorter cycle period, such as forming or drawing processes, then full annealing would be a good choice (Mudda et al., 2025). Finally, there is process annealing, which provides yet another advantage. Process annealing mainly reduces hardness and increases ductility of cold-worked low-carbon steels. Process annealing utilizes a lower temperature and duration compared to the other two processes (Bharti et al., 2020). This process is suitable when the objective is to soften the metal for deformation purposes. It is not intended to change the shape of the carbides; hence, it cannot lead to round carbides and other machining advantages provided by spheroidizing annealing.

7.1. Literature Base Case Study on Industrial and Structural Application

- Full annealing is widely used in preparing automotive components such as gears, shafts, and brackets. According to literature reported by Onwudili & Iweka (2021), full annealing reduces hardness from 250 HV to about 165 HV. This lower hardness allows efficient cold forming of transmission components without cracking. Controlled furnace cooling increases ductility by 25–30%. This improvement makes the parts suitable for later machining.
- In continuous wire-drawing operations (Amos et al., 2018), the study showed that process annealing restores ductility in high-carbon wires after each drawing pass. This prevents fracture and greatly improves formability. Process annealing at about 650°C also minimizes residual stresses. As a result, the dimensions of thin sheet metal used in the electrical and appliance industries remain consistent.
- Among annealed steels, spheroidized steels are most suitable for high-speed machining. They have lower hardness and provide very good machinability. According to, spheroidized eutectoid steel reduces tool wear by 40–50% during milling of bearing rings. The rounded carbides formed by prolonged subcritical heating improve surface finish and reduce cutting forces.

Each one of these annealing processes has advantages in being chosen, depending on the needs, either industrially or structurally. Full annealing, process annealing and spheroidization annealing find their application in several industries to optimally enhance the mechanical properties of the materials industrially and structurally (Wu et al., 2023). Knowledge about the implications of each process in the choice decides proper treatments to meet the performance requirements needed for reliability and efficiency of parts in service.

7.1.1. Industrial Case Studies and Practical Examples

The choice of the annealing process in industry not only relies on the desired mechanical characteristics but is influenced by production considerations such as manufacturing efficiency, accuracy, energy use, and manufacturing processes that come afterwards. Therefore, there are various annealing methods applied depending on the particular needs of the eutectoid steel components.

Table 6. Industrial Applications of Annealing Processes for Eutectoid Steel (Skowronek et al., 2025; Sun et al., 2025; Cheng et al., 2015)

Annealing Process	Typical Industrial Application	Primary Objective	Key Benefit
Full Annealing	Forged shafts, gears, and machined components	Reduce hardness and residual stress	Improved machinability and dimensional stability
Process Annealing	Wire rods, fasteners, springs, cold-formed products	Restore ductility between deformation stages	Prevent cracking and improve formability
Spheroidizing Annealing	Bearing steels, tool steels, and high-carbon wire	Produce spheroidized carbides	Excellent machinability and cold formability

Case Study 1: Manufacturing of Bearing Steel

Spheroidizing annealing is widely used in the manufacturing of high-carbon bearing steels since a spheroidite structure results in better machining and cold forming before the heat treatment of the components. The resulting decrease in cutting stresses and tool wear allows for efficient machining of bearing rings and rolling elements in accurate dimensions. After machining, components are hardened and tempered for high hardness and fatigue strength properties.

Case Study 2: Wire Rods and Fasteners

Intermediate annealing is commonly performed in the manufacturing process of steel wire, springs, and fasteners, which undergo repeated processes of cold drawing and cold working. Annealing will restore the ductility of the metal in question through the mechanisms of recovery and partial recrystallization, thus minimizing work hardening and avoiding crack formation in subsequent deformations.

Case Study 3: Forged and Machined Parts

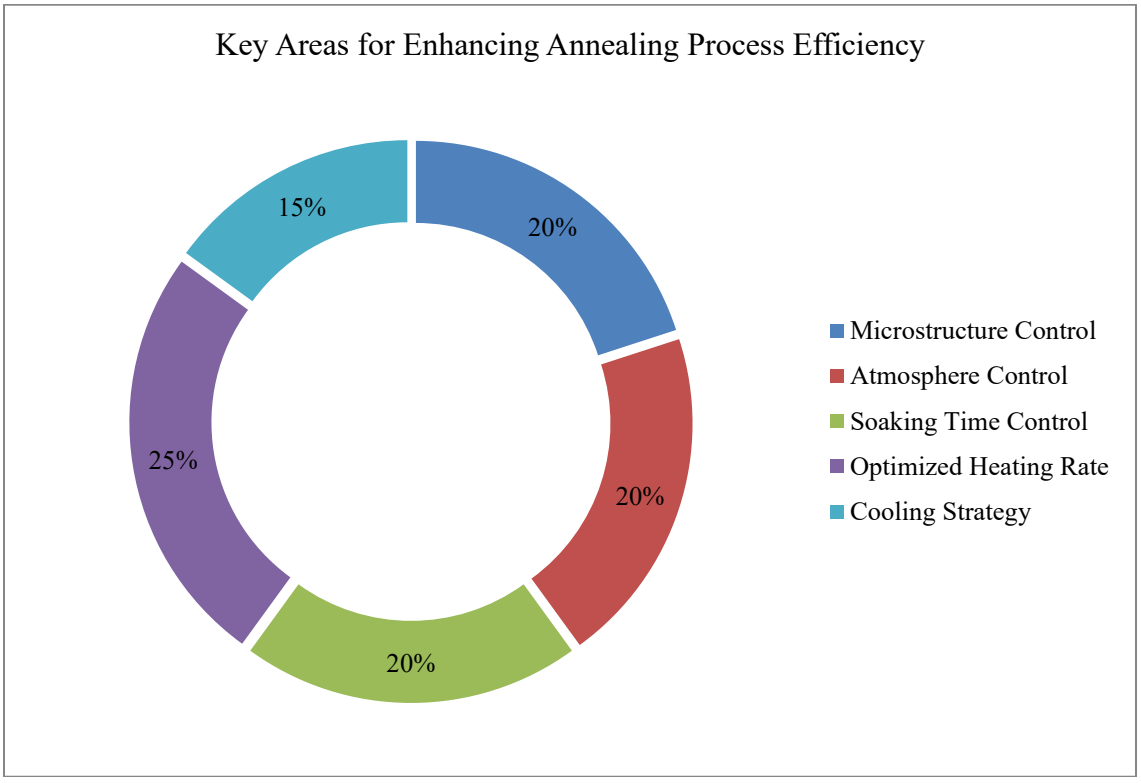
Annealing in the form of full annealing is regularly performed on forgings and hot-worked parts made of eutectoid steel. The slow cooling procedure in the furnace improves the microstructure, eliminates stresses, and lowers the hardness of the material, making it more machineable.

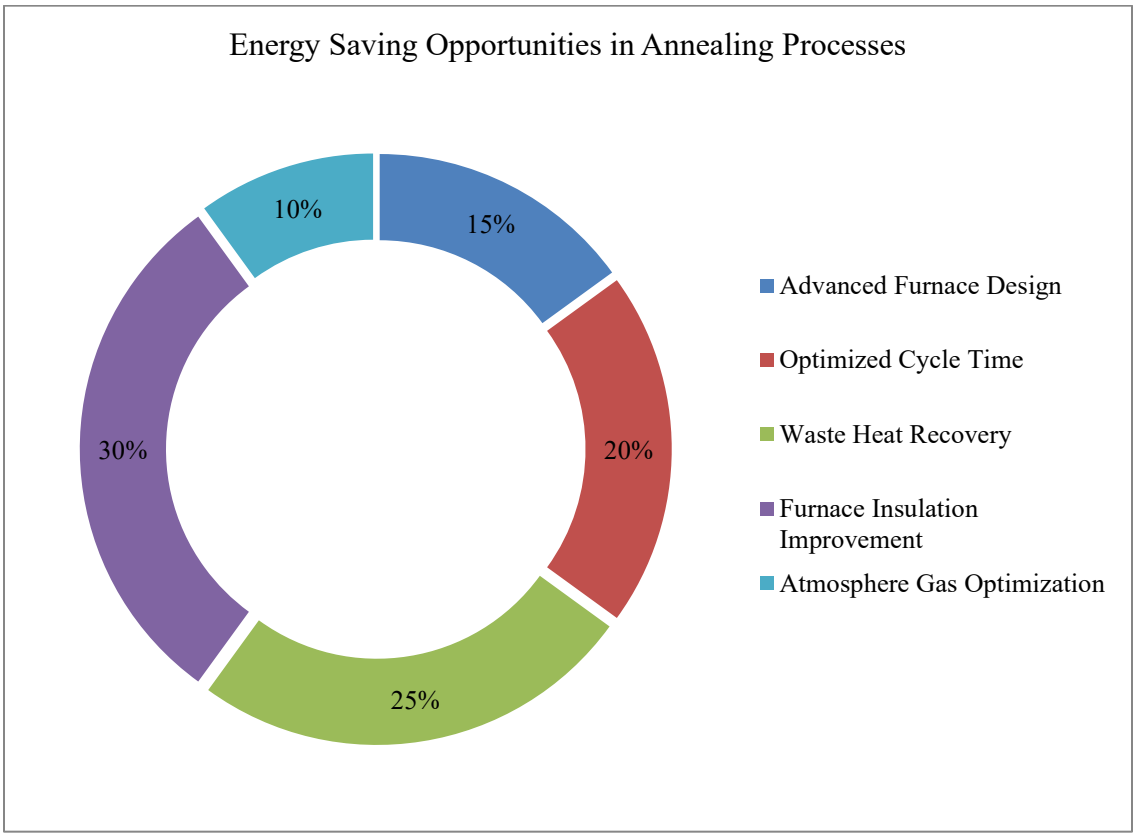
On the whole, the aforementioned industrial applications reveal that there is no universal method of annealing. The full annealing is suitable for reducing stresses and improving machinability of forgings, the process annealing is favorable for repeated cold-working treatments, and the spheroidizing annealing is applicable in case of high carbon steels when the highest degree of machinability and formability is needed.

8. Challenges and Future Directions

Annealing techniques have significant importance in optimizing the mechanical properties of different materials, e.g., reducing internal stresses in materials. However, there are still some challenges in the annealing process.

The Fig. 11 is developed by the authors based on their extensive survey of literature and market survey, which states that factors such as increase in heating rate (25%), increase in soaking time (20%), control of atmosphere (20%), control of microstructure (20%), and increase in cooling rate (15%) improve the efficiency of the annealing process, whereas factors such as reduction in energy costs (30%), reduction in waste heat (25%), optimization of annealing process (20%), design of furnace (15%), and control of cost of gases used in atmosphere (10%) improve the energy savings, whereas factors such as reduction in energy costs (30%), reduction in annealing times (25%), increase in yield with minimum rework (15%), reduction in maintenance costs (15%), and reduction in cost of gases used in atmosphere (15%) improve the cost reduction (Yi et al., 2012; Zheng et al., 2012; Zhang et al., 2025).





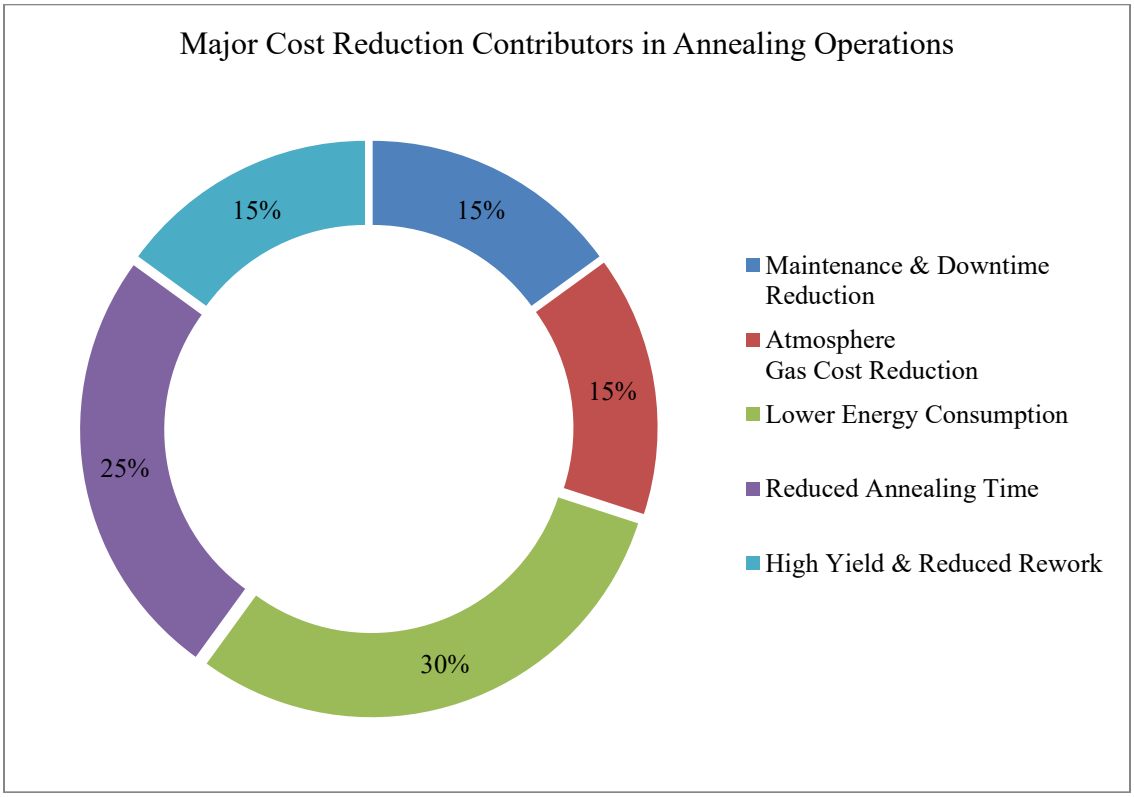


Fig. 11 Pie Chart on Major Key Important Area to Improve Annealing Process Efficiency, Energy Saving and Cost Reduction

The conventional spheroidizing annealing process is still very energy-intensive and time-consuming, requiring 10-50 hours. Optimization of the process is sensitive to temperature fluctuations. However, the decarbonization and oxidation problems, especially in coil packages, are still significant. The nitrogen atmosphere makes the problems worse, but the hydrogen atmosphere has its own problems, which are related to safety and cost considerations. Distortion is also possible in the case of full annealing, especially in longer lengths, due to non-uniform heating, causing instability in the dimensions of the machined part. Non-uniform spheroidization is another problem in thick coil packages due to inadequate circulation and temperature gradients, resulting in the formation of 10-20% spheroidite. Annealing is responsible for 30-45% of the total heat treatment energy consumption in the steel industry. Hence, there is a need to optimize the annealing process. There is no feedback mechanism in the industrial annealing process, and the potential of AI/ML-based predictive models is still not being utilized properly, although there is evidence of saving up to 10-25% in time and energy consumption (Zheng et al., 2014; Zhang et al., 2025). Recent emerging studies on the subject include the integration of annealing with thermomechanical processing, cyclic heating, and cryogenic treatments (Saha et al., 2010; Szala et al., 2020; Tressia et al., 2025; Su et al.,2019). These studies have been carried out with the objective of enhancing the properties of microstructures, hardness, strength, and wear resistance. For example, warm deformation combined with eutectoid transformation is employed to reduce the spheroidizing process, which results in ultrafine carbides (Qin & AuthorN, 2024; Strakosova et al., 2022). Hybrid treatments, rapid heating treatments, Localized treatments and modeling-based treatments have been invented for reducing energy consumption. These treatment processes have been invented in order to fulfill sustainability demands. Future research on the subject should include atomistic modeling, composition of gases, diffusion modeling, energy consumption in industries, carbide stability map, and physics-based machine learning modeling. These results will be used to obtain optimal conditions. It is very important to integrate annealing with other treatments in order to meet performance requirements in modern industrial processes.

9. Conclusion

The current paper provides a critical comparative evaluation of the major types of annealing, which include full annealing, process annealing, and spheroidizing annealing of the eutectoid steel. Each type possesses a different thermal processing cycle, structure formation, and properties. Moreover, all types are applied in practice. In the current work, the comparative evaluation of full annealing, process annealing, and spheroidizing annealing is presented, explaining the principles of operation and advantages in practice. As a result of the full annealing, the coarse pearlitic structure appears, providing the maximum ductility of steel (Skowronek et al., 2025). The process is widely applied for manufacturing the elements of cars, pressure pipes, and deep-drawn products (Skowronek et al., 2025). Process annealing removes the internal stress and improves the formability of the cold-worked steels (Sun et al., 2025). The process is used in continuous wire drawing, sheet metal forming, and mass production (Mudda et al., 2025). Spheroidizing annealing provides the uniform formation of rounded carbides, ensuring the high machinability and stability of the dimensions of the parts. The process is applied for the treatment of tool steels, bearings, dies, and machining parts (Mishra et al., 2017).

Present annealing processes are severely constrained by high energy, long annealing cycle times (predominantly in spheroidization) and poor flexibility to changing steel compositions. Future research on eutectoid steel annealing should focus on several important gaps. Some of the promising answers to these are:

- Carbide spheroidization is still slow. This limits productivity. Faster methods such as cyclic heating–cooling, quicker isothermal treatments, and diffusion modeling should be tested (Yi et al., 2012; Wu et al., 2023). These methods may reduce cycle time without harming carbide shape.
- Hybrid atmospheres are becoming increasingly used. The topic requires additional research. It is necessary to consider issues of carburization rate, decarburization rate, oxide stability and environmental effects. Research efforts may lead to higher annealing efficiency and more uniform microstructure.
- There are significant differences between furnaces. It illustrates the necessity of real-time process control (Saha et al., 2010). Machine learning algorithms based on sensors' data might be capable of predicting hardness, fraction of spheroidite and energy consumption.
- Artificial intelligence and machine learning integration into annealing technology is likely to improve real-time optimization and predictions, as well as process control and consistency (Lü et al., 2016).
- The effects of microalloying additions are not fully understood. Such elements as Mn, Si, Nb and Mo affect pearlite dissolution and carbide formation (Durgaprasad et al., 2017). They may be investigated by means of SEM/TEM annealing tests.
- Sustainable processes, alternative atmospheres and heat recovery methods will significantly reduce the environmental effects of annealing.

Last but not least, annealing continues to be the backbone of steel heat treatment. Material requirements served by precision production, clean technology and budgetary limitations. All future progress should resolve metallurgical properties with energy efficiency, process control, and sustainability. Materials science and clean engineering advancements will define the next generation of annealing, optimizing the characteristics of eutectoid steel to further make it a versatile, flexible, and cleaner material for the future industry.

References

[1] Harshad Kumar Dharamshi Hansraj Bhadeshia, "Steels for Bearings," *Progress in Materials Science*, vol. 57, no. 2, pp. 268-435, 2012. [CrossRef] [Google Scholar] [Publisher Link]

[2] U.V. Opara et al., "Effects of Annealing Heat Treatment on the Mechanical and Microstructural Characteristics of Medium Carbon Steel," *Academic Journal of Science, Engineering and Technology*, vol. 10, no. 3, pp. 33-45, 2025. [Publisher Link]

[3] William D. Callister, and David G. Rethwisch, *Materials Science and Engineering: An Introduction*, 10th ed., Hoboken, NJ, USA: Wiley, 2018. [Google Scholar] [Publisher Link]

[4] S. Inthidech, and Y. Matsubara, "Effects of Carbon Balance and Heat Treatment on Hardness and Volume Fraction of Retained Austenite of Semi-Multi-Alloyed White Cast Iron," *International Journal of Metalcasting*, vol. 14, no. 1, pp. 132-143, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[5] Nicole Wielki, Noémie Heinz, and Daniel Meyer, "Characterizing the Local Material Properties of Different Fe–C–Cr-Steels by using Deep Rolled Single Tracks," *Materials*, vol. 13, no. 21, pp. 1-14, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[6] Ş. Baday, H. Başak, and A. Güral, "Analysis of Spheroidized AISI 1050 Steel in Terms of Cutting Forces and Surface Quality," *Kovove Materialy*, vol. 54, no. 5, pp. 315-322, 2016. [CrossRef] [Google Scholar] [Publisher Link]

[7] Valentin Pricop, Elena Helerea, and Marius Daniel Calin, "Influence of Alloy Elements on Magnetic Properties of Electrical Steels," *2016 International Conference on Applied and Theoretical Electricity (ICATE)*, Craiova, Romania, 2016. [CrossRef] [Google Scholar] [Publisher Link]

[8] Chenglong Sun et al., "Effects of Annealing Processes on Microstructure and Properties of FeNi-Based Amorphous Alloy," *Materials*, vol. 18, no. 13, no. 1-12, 2025. [CrossRef] [Google Scholar] [Publisher Link]

[9] Adam Skowronek et al., "Continuous Annealing of Medium-Mn Steels: Sensitivity of Mechanical Performance to Minor Changes in Time–Temperature Heat Treatment Parameters," *Materials Science and Engineering A*, vol. 940, pp. 1-15, 2025. [CrossRef] [Google Scholar] [Publisher Link]

[10] David A. Porter, and Kenneth E. Easterling, and Mohamed Y. Sherif, *Phase Transformations in Metals and Alloys*, 4th ed., CRC Press, 2009. [CrossRef] [Google Scholar] [Publisher Link]

[11] H. Rastegari, Ahmad Kermanpur, and Abbas Najafizadeh, "Effect of Initial Microstructure on the Work Hardening Behavior of Plain Eutectoid Steel," *Materials Science and Engineering A*, vol. 632, pp. 103-109, 2015. [CrossRef] [Google Scholar] [Publisher Link]

[12] Anthony Edozie Onwudili, and Sunday Chukwuka Iweka, "Full-Annealing and Its Effect on the Mechanical Properties of Alloy 304H Stainless Steel," *Journal of Engineering Research and Reports*, vol. 20, no. 7, pp. 1-17, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[13] Z. Nasiri, and H. Mirzadeh, "Spheroidization Heat Treatment and Intercritical Annealing of Low Carbon Steel," *Journal of Mining and Metallurgy, Section B: Metallurgy*, vol. 55, no. 3, pp. 405-411, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[14] A.V. Adedayo, S.A. Ibitoye, and O.A. Oyetoyan, "Annealing Heat Treatment Effects on Steel Welds," *Journal of Minerals and Materials Characterization and Engineering*, vol. 9, no. 6, pp. 547-557, 2010. [Google Scholar]

[15] Víctor Alcántara Alza, "Spheroidizing in Steels: Processes, Mechanisms, Kinetic and Microstructure - A Review," *IOSR Journal of Mechanical and Civil Engineering*, vol. 18, no. 3, pp. 63-81, 2021. [Google Scholar] [Publisher Link]

[16] P.G. Kubendran Amos et al., "Mechanisms of Pearlite Spheroidization: Insights from 3D Phase-Field Simulations," *Acta Materialia*, vol. 161, pp. 147-158, 2018. [CrossRef] [Google Scholar] [Publisher Link]

[17] Sheel Bharti et al., "Effect of Heat Treatment Processes on Metals and Alloys-A Review," *International Journal of Advanced Production and Industrial Engineering*, vol. 5, no. 2, pp. 54-63, 2020. [Google Scholar]

[18] Matteo Caruso, and Stéphane Godet, "Microstructural Evolution During Spheroidization Annealing of Eutectoid Steel: Effect of Interlamellar Spacing and Cold Working," *Advanced Materials Research*, vol. 89-91, pp. 79-84, 2010. [CrossRef] [Google Scholar] [Publisher Link]

[19] Cheng Ji, Lei Wang, and Miao-yong Zhu, "Effect of Subcritical Annealing Temperature on Microstructure and Mechanical Properties of SCM435 Steel," *Journal of Iron and Steel Research International*, vol. 22, no. 11, pp. 1031-1036, 2015. [CrossRef] [Google Scholar] [Publisher Link]

[20] Feng Zhiming, and Yang Wangyue, "Spheroidized Fine Structure by Cold Rolling and Annealing of Eutectoid Pearlite Steel," *Journal of University of Science and Technology Beijing*, vol. 29, no. 7, pp. 689-693, 2007. [CrossRef] [Publisher Link]

[21] A. Durgaprasad et al., "Microstructures and Mechanical Properties of as-Drawn and Laboratory Annealed Pearlitic Steel Wires," *Metallurgical and Materials Transactions A*, vol. 48, no. 10, pp. 4583-4597, 2017. [CrossRef] [Google Scholar] [Publisher Link]

[22] Azdiar A. Gazder, Sujoy S. Hazra, and Elena V. Pereloma, "Annealing Behaviour and Mechanical Properties of Severely Deformed Interstitial Free Steel," *Materials Science and Engineering A*, vol. 530, pp. 492-503, 2011. [CrossRef] [Google Scholar] [Publisher Link]

[23] E.S. Gorkunov et al., "Structure and Mechanical Properties of a High-Carbon Steel Subjected to Severe Deformation," *Physics of Metals and Metallography*, vol. 118, no. 10, pp. 1006-1014, 2017. [CrossRef] [Google Scholar] [Publisher Link]

[24] Wanhui Huang et al., "Microstructure and Mechanical Properties of Multi-Pass Forged and Annealed 42CrMo Steel," *Materials Science and Engineering A*, vol. 831, 2022. [CrossRef] [Google Scholar] [Publisher Link]
[25] Anthony Rollett et al., *Recrystallization and Related Annealing Phenomena*, 2nd ed., Oxford, U.K.: Elsevier, 2004. [Google Scholar]
[26] Sujit A. Jagnade et al., "Optimization of Continuous Steel Annealing Operations using Model Predictive Control at Tata Steel, India," *INFORMS Journal on Applied Analytics*, vol. 55, no. 1, pp. 48-65, 2025. [CrossRef] [Google Scholar] [Publisher Link]
[27] Erdal Karadeniz, "Influence of Different Initial Microstructure on the Process of Spheroidization in Cold Forging," *Materials & Design*, vol. 29, no. 1, pp. 251-256, 2008. [CrossRef] [Google Scholar] [Publisher Link]
[28] Zhi-qing Lü et al., "Effect of Cyclic Annealing on Microstructure and Mechanical Properties of Medium Carbon Steel," *Journal of Iron and Steel Research International*, vol. 23, no. 2, pp. 145-150, 2016. [CrossRef] [Google Scholar] [Publisher Link]
[29] Shakti Mishra et al., "Accelerated Lamellar Disintegration in Eutectoid Steel," *Philosophical Magazine Letters*, vol. 97, no. 4, pp. 140-149, 2017. [CrossRef] [Google Scholar] [Publisher Link]
[30] Sharan Mudda et al., "Effect of Various Heat Treatment Methods and Optimization of Their Parameters on Mechanical Properties of AISI 4140 Steel," *Scientific Reports*, vol. 15, pp. 1-9, 2025. [CrossRef] [Google Scholar] [Publisher Link]
[31] James M. O'Brien, and William F. Hosford, "Spheroidization in Medium-Carbon Steels," *Journal of Materials Engineering and Performance*, vol. 6, no. 1, pp. 69-72, 1997. [CrossRef] [Google Scholar] [Publisher Link]
[32] J.R. Páez et al., "A Microstructure-based Constitutive Model for Eutectoid Steels," *Acta Materialia*, vol. 263, pp. 1-14, 2024. [CrossRef] [Google Scholar] [Publisher Link]
[33] Mirosław Szala et al., "Effect of Annealing Time and Temperature Parameters on the Microstructure, Hardness, and Strain-Hardening Coefficients of 42CrMo4 Steel," *Materials*, vol. 13, no. 9, pp. 1-16, 2020. [CrossRef] [Google Scholar] [Publisher Link]
[34] G. Tressia et al., "Enhancing Wear Resistance and Mechanical Properties of Eutectoid Pearlitic Steel through Low-Temperature Annealing: Microstructural Transformations and Performance Implications in Railway Applications," *Materials Research*, vol. 27, pp. 1-14, 2024. [CrossRef] [Google Scholar] [Publisher Link]
[35] Sheng-Rui Su et al., "The Novel Process of Spheroidizing-Critical Annealing used to Optimize the Properties of Carburized Steel and its Effect on Hardening Mechanism of Quenching and Tempering," *Materials Science and Engineering A*, vol. 765, 2019. [CrossRef] [Google Scholar] [Publisher Link]
[36] Vitaliy Vlasovets et al., "Improving the Performance Properties of Eutectoid Steel Products by a Complex Effect," *Materials*, vol. 15, no. 23, pp. 1-14, 2022. [CrossRef] [Google Scholar] [Publisher Link]
[37] Zhonglin Wu et al., "Effects of Different Annealing Time on Microstructure and Mechanical Properties of Lightweight Al-Containing Medium-Mn Steel," *Ironmaking & Steelmaking: Processes, Products and Applications*, vol. 50, no. 11, pp. 1726-1736, 2023. [CrossRef] [Google Scholar] [Publisher Link]
[38] Hongliang Yi et al., "Acceleration of Spheroidization in Eutectoid Steels by the Addition of Aluminum," *Scripta Materialia*, vol. 67, no. 7-8, pp. 645-648, 2012. [CrossRef] [Google Scholar] [Publisher Link]
[39] Hailong Zhang et al., "Novel Process used to Accelerate Spheroidizing Annealing of Gcr15 Bearing Steel by Modulating Initial Structure," *Materials Today Communications*, vol. 44, 2025. [CrossRef] [Google Scholar] [Publisher Link]
[40] Chengsi Zheng et al., "Enhancement of Mechanical Properties by Changing Microstructure in the Eutectoid Steel," *Materials Science and Engineering A*, vol. 558, pp. 158-161, 2012. [CrossRef] [Google Scholar] [Publisher Link]
[41] Atanu Saha, Dipak Kumar Mondal, and Joydeep Maity, "Effect of Cyclic Heat Treatment on Microstructure and Mechanical Properties of 0.6wt% Carbon Steel," *Materials Science and Engineering A*, vol. 527, no. 16-17, pp. 4001-4008, 2010. [CrossRef] [Google Scholar] [Publisher Link]
[42] Fengming Qin et al., "Static Recrystallization Behavior and Twin Formation Mechanism of Fe–Mn–Cr–N Steel During Medium Temperature Annealing," *Metallurgical and Materials Transactions A*, vol. 56, no. 1, pp. 228-240, 2024. [CrossRef] [Google Scholar] [Publisher Link]
[43] Angelina Strakosova et al., "Annealing Response of Additively Manufactured High-Strength 1.2709 Maraging Steel Depending on Elevated Temperatures," *Materials*, vol. 15, no. 11, pp. 1-12, 2022. [CrossRef] [Google Scholar] [Publisher Link]