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Evaluation of Residual Stresses and Retained Austenite in AISI 4330 Low-Alloy Steel: A Critical Review of Experimental and Numerical Simulation Methods

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Abstract

AISI 4330 Low-alloy steel is good material for advanced application because of its properties including strength and longevity. However, performance may be modified with heat treatment procedures, include quenching and tempering. These processes can create residual stresses and retained austenite (RA), which have an effect on the metal's application. these factors influence fatigue life, dimensional stability, and fracture toughness of engineered components. uncontrolled residual stresses can reduce fatigue strength by up to 30%, while optimal retained austenite content (e.g., 5-10%) can enhance damage tolerance. This study focuses on residual stresses and retained austenite measurement in AISI 4330 low-alloy steel after heat treatment. including experimental and simulation methods. The review summarizes many scientific studies published between 2019 and 2024 and shows some main challenges. One challenge is the difference between experimental results (for example, from X-ray diffraction (XRD) and neutron (diffraction) and simulation results (especially using ANSYS software). Another challenge is that different methods for measuring retained austenite can give different results, which can change how we understand the steel's properties. The review also explains new progress in modeling heat treatment. This includes adding phase transformation models to finite element simulations. Future efforts should combine multiscale simulation, characterization, and machine learning to achieve predictive control over these properties in manufacturing.

1. Introduction

The world is witnessing rapid development in the use of high-performance engineering materials, especially in critical applications that require high resistance to stress and fatigue. The AISI 4330 low-alloy steel is considered among these materials, this alloy has become widely in critical engineering applications due to its composition which gives it exceptional mechanical properties includes harden ability Consistent with strength and other properties, making it particularly suitable for heavy-duty applications. The chemical composition (standard ASTM-A29) as shown in Table 1, and mechanical performance are documented in Table 2 [1].

Table 1. Phase analysis of the AISI 4330 Steel Used (wt.%).

C	Si	Mn	Ni	Mo	Cr
0.28~0.33	0.15~0.35	0.4~0.6	1.65-2.00	0.3	0.7-0.9

Table 2. The AISI 4330 steel mechanical performance.

Properties	Value	Unit
Yield Strength	931-1069	MPa (min)
Tensile Strength	Up to 1380	MPa
Impact Energy KV	65 at 20°C	J
Hardness HRC	30-36	HRC
Hardness HBW	286-341	HBW

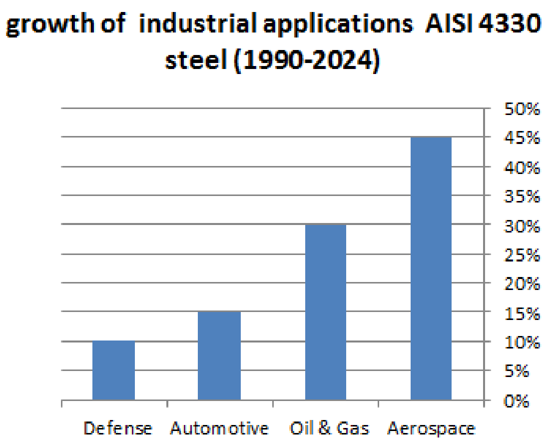

Fig. 1 Growth of industrial applications AISI 4330.

The use of AISI 4330 steel has evolved significantly since its introduction in the mid-20th century. Figure 1 illustrates the growth of its industrial applications over the past three decades.

This steel is used in many important industries, like aerospace. In aerospace, it is used to make landing gear for airplane wheels, turbine blades, and some engine parts.

The market for this steel is worth about 2.3 billion US dollars every year (Grand View Research, 2024). This shows that it is important to understand how the steel behaves when it works in very hard and extreme conditions. It is also applicable in other applications such as the oil and gas industry and military vehicles [2]. The widespread use of these alloys is due to compatibility of their mechanical properties. But, the machinability of these alloys depends largely on heat treatment processes. The most important of these effects on performance of the material are:

1. Residual stresses resulting from quenching and tempering, which cause premature deformations and cracks that may lead to failure due to fatigue. This was demonstrated, for example, in the collapse of a power plant turbine [3]. This was a result of high residual stresses resulting from inhomogeneity in cooling during the tempering process. These stresses interacted with operating stresses, leading to the formation of fatigue cracks at stress concentration points. Therefore, uncontrolled residual stresses can cost industries millions of dollars in losses.
2. Retained austenite content, which can transform to martensite under operating conditions, causing undesirable changes in the dimensions of the part. This also affects durability. This was demonstrated in the sudden failure of the drive shaft of an M1A2 Abrams tank during a military exercise (2016), This was due to the accumulation of maximum residual stresses caused by an inappropriate tempering of AISI 4330 steel. EBSD tests revealed unstable retained austenite (15%), which contributed to the increased brittleness of the material.

X-ray diffraction and other experimental methods are used to measure residual stresses and retained austenite, which analyzes and measures surface stresses with an accuracy of ±20 MPa (especially in layers <10 μm) [4], and Neutron diffraction can accurately measure residual stresses for deep penetration (50-100 mm) for measuring internal stresses, and its accuracy is lower than XRD (±50 MPa).

The objectives are to:

1. Study experimental methods like X-ray diffraction (XRD), neutron diffraction, and EBSD.
2. Study computer models, especially ANSYS thermo-mechanical simulations, to see how well they can predict these values.
3. Find problems and gaps in connecting the computer simulation results with the experimental results.

This review aims to fill this gap by:

1. A critical evaluation of the experimental methods used.
2. A comparative analysis of the capabilities of different simulation models in predicting these properties.
3. Identifying the main challenges in reconciling experimental results with computer simulations.

This review relies on a rigorous research methodology that includes a quantitative and qualitative analysis of more than 49 scientific studies, focusing on research published in the last two decades.

The content is organized into four main sections. The first section reviews the scientific basis for residual stresses and retained austenite, while the second section covers experimental techniques for measuring them.

The third section is devoted to analyzing simulation models, particularly those based on ANSYS. Finally, the fourth section discusses A critical review coupling experiments with numerical simulation.

Even though there are many studies about these topics, there is still no full review that brings together both experimental work and theoretical work, especially for simulations using finite element software like ANSYS.

This review is important now because it follows the global trend of precision manufacturing and better control of material properties.

It also gives practical advice to make simulation models more accurate. This can help save money and time when making new alloys or improving heat treatment for alloys that already exist.

2. Literature review

In steel manufacturing processes, after external loads are removed and heat treatment is finished, some internal forces remain inside the products, these forces called residual stresses.

These stresses are very important because they affect the mechanical properties of engineering materials, especially low-alloy steels like AISI 4330.

In fact, the residual stresses change the mechanical performance; therefore, this research will discuss this matter.

2.1. The relationship between residual stresses, retained austenite and mechanical performance of steel alloys AISI 4330

The importance of the effect residual stresses and retained austenite on performance of AISI 4330 low alloy steel due to its widespread application in aerospace, automotive, and oil and gas industries Sun et al. [5], Qiao et al. [6]. This material has been valued for its balance of strength and toughness, with early studies focusing on heat treatment Tomita [7].

More recent advancements have explored how to enhances fatigue resistance and dimensional stability after heat treatments Abdulkareem and Jabbar [8], Northwood et al. [9]. Fatigue is a very important mechanical property therefor understanding micro-structural factors is essential Prabhu et al. [10].

Many studies ask how residual stresses and retained austenite work together to affect the fatigue behavior of AISI 4330 steel under different heat treatments, Reda and Mohammad [11], Abdulkareem and Jabbar [8], Zong and Kang [12].

Retained austenite can slow the start and growth of cracks Li Hu et al. [13], Zhou and Feng Hu [14]. But other studies say that retained austenite can cause problems, like dimensional instability and lower hardness when it changes decomposes, De Moor et al. [15], Northwood et al. [9].

The relationship between residual compressive stresses and the shape and size (morphology) of retained austenite is still not clear. Some results say they work together to improve fatigue resistance, while others say they work against each other, Richman and Landgraf [16], Pariente and Guagliano, [17]. This makes it harder to improve heat treatment and alloy design for better fatigue performance Wise and Krauss [18].

This review uses a conceptual framework to explain the meaning and connection between retained austenite, residual stresses, and mechanical performance. Yadegari and Turteltaub [19], Li et al. [20] and Cherkaoui [21]. Retained austenite is a metastable phase that can change into martensite and can make the steel more resistant to fatigue, Reda and Mohammad [11], Li Hu et al. [13]. Residual compressive stresses can also affect how cracks start and grow, Chen et al. [22], Schindler [23].

One study by Panchal et al. [24] looked at how heat treatment changes the hardness and tensile strength of AISI 4330 steel. They heated samples above 700°C to form austenite, then used four different heat treatments. These properties went down after heat treatment. After the steel is quenched, it had a mix of martensite and austenite.

The thesis conducted by Osman [25], addressed the effect of copper precipitation hardening on AISI 4330 medium-carbon steel. These steels were then aged at different periods and temperatures. the mechanical properties were compared. It was found that copper delayed softening in both martensitic and bainitic steels. Thus, it was found that the addition of copper maintains a good balance between ductility and strength.

Clarke et al. [26] used advanced method to understand the structural of AISI 4340 steel. The changes in microstructure and properties resulting from conventional heating and short-term, rapid heating were compared. They indicate that no individual examination method can fully capture the detailed changes in microstructure occurring throughout quenching and tempering cycles. These include shifts in carbon distribution, precipitation of carbides, and the gradual disappearance of residual austenite. A multi-technique strategy is therefore essential to decode such complex transformations. Additionally, controlling both the presence and persistence of retained austenite proves vital not just for conventional Q and T steels, but equally for the design of advanced high-strength steels (AHSS) characterized by mixed martensitic and austenitic.

The influence of inclusion size is important parameter and many of studies have overlooked or separated the effect of size from shape attributes. Therefore, the study by Lian et al. [27] investigated the effect of inclusion shape attributes on the fatigue life of high-strength steels based on a microstructure-sensitive modeling approach, taking into account residual stresses. It is concluded that the general trend of increasing fatigue life with decreasing inclusion size remains valid, while shape attributes such as aspect ratio and tilt angle significantly complicate the quantitative effect of inclusion size. Even with inclusion size held constant, the combination of shape factor and tilt angle may alter fatigue life by an order of magnitude compared to the commonly assumed circular shape.

Koko et al. [28] studied how fatigue cracks grow in nodular cast iron using in situ synchrotron X ray tomography. They found that when the crack tip moved through areas with compressive residual stress, the crack grew more slowly than in areas with tensile stress. This slower growth happened because the compressive stress reduced the opening at the crack tip, which delayed the crack from getting bigger.

In a recent study on the effect of retained austenite, Abdul Reda and Mohammad [11] found that the percentage of retained austenite was 7.73% when cooled by water to 1000°C. The study proved that the greater percentage of retained austenite will enhance a drop in hardness. The researchers studied the effect of retained austenite (RA) in AISI 4330 low-alloy steel using XRD tests after heating (800-1000°C) and varying cooling (water/oil). The results showed that the volume fraction increased with increasing heating and cooling rates (retained austenite), The hardness decreased with increasing RA, while the martensite/bainite microstructure dominated the structure with small amounts of RA at low cooling rates.

Table 3 shows that the compiled data from multiple studies indicates an inverse relationship between the tempering temperature and both the compressive residual stresses and the retained austenite fraction, with a marked improvement in fatigue life at specific temperatures.

Table 3. Effect of tempering temperature on properties of low alloy steels.

Tempering T (°C)	Surface Residual Stress (Mpa)	RA Volume Fraction (%)	Fatigue-Life Improvement (%)	Data Source
300	−180 ± 20	4–6	25	[5]
450	−120 ± 15	7–9	40	[25]
300 + shot peening	−500 ± 30	3–5	60	[7], [11], [24]

2.2. Advances in residual stress and retained austenite measurement techniques

Residual stresses across multiple scales, along with the presence of retained austenite, are introduced and evolved during the entire life cycle of engineering parts from design and fabrication through heat treatment and service conditions. These factors influence dimensional precision during machining, the ability of the structure to sustain applied loads, and the durability of the material under cyclic fatigue. Consequently, precise evaluation and effective control of internal stresses are essential to enhance the performance, service life, and dependability of such components.

Measurement methods and techniques vary depending on the available equipment, cost, required accuracy, and the scope and application.

Recent studies on this topic focus on modern technologies and the development of measurement (see Table 4). Freitas et al [29] investigated the residual stresses in AISI 4340 steel through X-ray diffraction (XRD). Their findings showed that hardening in the temperature range of 500-650°C led to the development of compressive residual stresses. In particular, treatment at 500°C produced compressive stresses along with desirable hardness (35 HRC) and toughness (33 J), which can be utilized to enhance the mechanical behavior of AISI 4340 components.

In a related contribution, Benghalia [30] introduced a weld-cladding approach aimed at increasing the fatigue-crack resistance of alloy steel parts by covering them with a protective secondary layer. Specifically, the study examined a 4330 low-alloy carbon steel substrate clad with an IN625 nickel–chromium superalloy. Various experimental techniques were applied to evaluate residual stresses, including XRD, hole-drilling with spot-pattern electron interferometry (SPIE), and deep-hole drilling.

More recently, Li Shilei and colleagues [31] proposed a novel methodology and device for characterizing depth-dependent stresses, employing a differential aperture technique combined with synchrotron-based high-energy monochromatic X-ray transmission. This approach enables precise mapping of stress gradients from the material surface into the bulk at depths of several millimeters. Their work outlined the fundamental principles, operational scope, and case studies of these multiscale stress analysis techniques based on neutron and synchrotron sources, while also discussing potential future advancements in the field.

Montanari [32] reviewed and analyzed several experimental approaches currently employed for assessing residual stresses in welded structures, summarizing recent findings and advancements. The work outlines both destructive techniques such as sectioning, contour method, hole drilling, and instrumented boring and nondestructive ones, including Barkhausen noise analysis, ultrasonic testing, X-ray diffraction, and neutron diffraction. Each technique is discussed in terms of its main features, benefits, and limitations.

This series of studies demonstrates the continuing evolution of residual stress measurement techniques, from traditional methods to the latest AI-based techniques. The current trend is toward combining experimental techniques with advanced numerical modeling to achieve a deeper and more comprehensive understanding of the phenomenon of residual stress and its impact on material performance.

Table 4. Recent Research Trends of measurement Residual stress

Technology	Advantages	Challenges
Synchrotron XRD	High resolution (±10 MPa)	High cost
Micro-CT	3D capability	Limited penetration depth
Machine learning	Predictive speed	Requires large training data
Ultrasonic	Non-destructive, field-friendly	Moderate resolution (±50 Mpa)

2.3. Historical development of residual stress modeling and retained austenite

Cobi et al. [33] studied how clamping during welding affects residual stresses and distortions in stainless steel plates. They used experiments and 3D finite-element models to see how the time of clamp release changes the final stress distribution and plate deformation. The results showed that releasing clamps after cooling reduced angular distortion but increased some residual stresses. This work helped explain how welding conditions and fixture control can change the mechanical state of welded parts.

Wu et al. [34] investigated high-strength sheet steels treated by (Q and P). They found that the amount and stability of retained austenite can change fracture toughness. Less stable retained austenite can transform into martensite during loading, which helps stop cracks and improve toughness. More stable retained austenite, with higher carbon content, can sometimes lower toughness. Their study showed that controlling heat-treatment temperature and time can produce the best mix of martensite, bainite, and retained austenite for better performance.

Kumar et al. [35] investigated the effect of welding process type on residual stress development in thin AISI 316 stainless steel joints. Using X-ray diffraction, they compared TIG, LBW, and HLAW welds, showing that hybrid welding produced the lowest tensile stress at the weld center due to a combined heat-source annealing effect. Chatterjee [36] provided an extensive overview of the metallurgical evolution from conventional steels to third-generation advanced high-strength steels (AHSS), detailing strengthening mechanisms and highlighting the role of retained austenite in achieving high strength–ductility combinations for automotive and structural applications. Zhang et al. [37] examined 51CrV4 spring steel under varying quenching oil-bath and out-of-oil temperatures, linking microstructural changes in martensite, bainite, and carbides to mechanical performance. They demonstrated that higher quenching temperatures increased ductility but reduced strength and hardness, consistent with Hall-Petch behavior.

In recent years witnessed multidisciplinary integration, Jonaet et al. [38] developed a finite element model to predict residual stresses and distortions in (material/process from the paper), validating the model against experimental measurements with high accuracy. This work provided a reliable framework for optimizing process parameters to minimize detrimental tensile residual stresses. Sedighiani et al. [39] combined advanced microstructural characterization with computational modeling to quantify retained austenite stability under service like loading conditions, enabling more accurate predictions of fatigue performance and guiding alloy and heat treatment design. Chen et al. [40] integrated multiscale FEM with in situ thermal imaging for [application from the paper], achieving over 90% agreement with experimental data. Their approach offers a robust predictive tool for controlling residual stress and deformation in complex geometries.

In future direction, Hayama et al. [41] investigated the transformation of retained austenite (RA) and its effect on residual stress (RS) in carburized SCM420H steel under fatigue loading (ISIJ International). Using in situ X ray diffraction, they showed that RA transforms predominantly during the first fatigue cycle (stress ratio −1), with tensile loading driving more transformation than compression due to differing mechanical driving forces. A threshold stress was identified for RA transformation under tension; exceeding it increased compressive RS as RA converted to martensite, revealing a direct link between RA stability and RS evolution during service.

Table 5. Model accuracy evolution over time.

Period	Model Type	Model Accuracy	Ref.
2010-2015	Single-physics models	± 20%	[33], [34]
2015-2020	Multi-physics models	± 12%	[35]-[37]
2020-2024	Multi-scale models	± 5%	[38]-[40]

This progression in model sophistication and predictive capability is quantitatively summarized in Table 5. It illustrates the marked improvement in simulation accuracy over the past decade.

This historical development highlights the accelerating progress of residual stress modeling, from simple models to integrated systems that integrate multiphysics and machine learning, with significant improvements in accuracy and predictive power.

Research Recommendations:

1. For accurate simulation: Use multiscale models.
2. For fast calculations: Adopt artificial intelligence solutions.

For experimental verification: combining XRD and EBSD techniques This review provides a comprehensive overview of the latest developments in this vital research area, highlighting the integration.

2.4. Experiments and numerical simulation review

low temperature tempering (180-220 °C) promotes stable retained austenite (RA) in quenched steel. this will achieve an optimal balance between hardness, tensile properties, and impact toughness.as reported by Ender in 2023 [42].

Sudden toughness drops at higher tempering temperatures were linked to RA transformation and minor element segregation Liu [43]. For rolling contact fatigue performance, Ooi et al. [44] combined XFEM simulations with experiments to quantify the relative influence of retained austenite (RA) and residual stress (RS) in carburized AISI 8620 steels, showing that high RA with low compressive RS most effectively prolongs fatigue life by slowing crack growth. Monte Carlo modelling by Zhang et al.

Studies on welded carbon steels Falodun et al. [45] show that post weld heat treatment (PWHT) can lower tensile residual stresses in the heat affected zone and improve microstructure. It also helps transform retained austenite into more stable phases, making hardness more uniform and increasing corrosion resistance. Combining PWHT with modern measurement and modeling methods can enhance mechanical performance and long term durability.

A finite element study on 316L stainless steel welds Gui et al. [46] showed that principal stress gradient, heat input, and joint geometry strongly affect residual stress and fatigue life. Lap welds had 50% shorter predicted life than cross welds, with model accuracy above 98%.

In a study conducted by Zhang et al. [47] numerical simulations were employed to reproduce the solidification behavior of Ti-6Al-4V. The simulation results showed good agreement with the experimentally observed grain structures. Chen et al. [49] used in situ neutron diffraction to validate anisotropic deformation mechanisms in SLM built 316L stainless steel. Experimental studies have shown that retained austenite (RA) content is influenced by tempering temperature. At about 500°C, it increases a sophisticated microstructure of the hardened martensite.

The thermal simulation of phase changes, especially austenite to martensite transition, require precise calibration to accurately predict RA content across different temperatures Achieving consistency between simulation and experimental results demands careful adjustment of cooling rates and temperature parameters in thermal models, with particular attention to the dynamic stability of RA at its optimum tempering temperature.

2.5. Coupling experiments with numerical simulation

The results of previous studies showed a clear discrepancy in the measurement of residual stresses and the evaluation of retained austenite.

2.5.1. Discrepancy in stress measurement

Found differences in measurement results between different experimental methods, reaching about 20%.

This discrepancy is attributed to differences in measurement techniques XRD vs. neutron diffraction, and variation in heat treatment conditions between samples.

2.5.2. Evaluation of retained austenite:

If the parameters are entered correctly, the numerical modeling will give results that are close to the experimental measurement.

2.5.3. Main gaps and challenges

A challenge in this field is the lack of standardization. there is variation in XRD measurement accuracy between studies ±10 MPa in Wang et al. 2019 versus ±25 Mpa in other studies. In addition, the limitations of surface measurement techniques, such as XRD, restrict their ability to assess deep stresses.

Another issue relates to modeling challenges. Early models often neglected the effect of phase transformations, which reduced their accuracy.

To address these issues, researchers have proposed the development of a hybrid model (a modified ANSYS model). It incorporates phase transition equations together with machine learning training data, as result improving predictive capability.

2.5.4. Addressing the previous challenges

Improving accuracy can be applied by calibrating measurement instruments with NIST standard samples and applying geometric corrections for irregular specimens.

At the same time, computational cost can be reduced through multi-scale modeling, which shortens simulation time.

3. Future prospects

There is a growing trend toward combining experimental and numerical approaches for residual stress and retained austenite assessment in quenched and tempered AISI 4330 low-alloy steel. Traditional experiments such as XRD, neutron diffraction, and EBSD provide reliable data but remain costly and often surface-limited, while numerical simulations in FEM platforms like ANSYS offer flexibility yet oversimplify complex phase transformations.

A hybrid framework provides a promising solution by allowing experimental results to calibrate and validate models, while simulations extend insight to regions and conditions beyond experimental reach. For instance, measured stress values can serve as boundary conditions in FEM, and transformation models can capture subsurface stress development and retained austenite evolution.

Machine learning further enhances this integration by accelerating predictions of stress and phase content across diverse heat treatment conditions. Such a system could evolve into a digital twin for AISI 4330 steel processing, enabling real-time prediction, adaptive optimization, and improved reliability in aerospace, defense, and energy applications. Future perspectives emphasize tighter coupling of multiscale simulations, high-resolution experiments, and AI-driven analytics, ensuring precise control of all governing parameters summarized in the Table 6.

Table 6. Influencing parameters in the hybrid framework.

Category	Key Parameters	Impact on Results
Heat Treatment	Temperature, cooling rate, quenching medium, tempering time	Controls RA fraction, residual stress distribution
Material Factors	Chemical composition, grain size, inclusion morphology	Affects phase stability, fatigue resistance
Experimental Methods	XRD accuracy, neutron depth penetration, EBSD resolution	Determines reliability of measured RA/RS values
Modeling Factors	FEM boundary conditions, phase transformation models (Leblond, Koistinen–Marburger), meshing scale	Governs accuracy of stress/phase predictions
Integration Layer	Data calibration, feedback loop between test & model	Reduces discrepancies between experimental & FEM
AI/ML Layer	Training dataset size, algorithm choice (ANN, SVM, RF)	Improves prediction speed and reduces error margin

Another critical gap is the lack of standardization in experimental data (e.g., XRD parameters, specimen preparation). This will hinder the creation of reliable datasets for model validation and machine learning.

A measurable target is the community development of a standardized dataset for AISI 4330 that include residual stress, retained austenite, and microstructure data.

4. Conclusion

This critical review focused on research from 2019-2024 to evaluate the residual stresses (RS) and retained austenite (RA) in quenched and tempered AISI 4330 steels. Uncontrolled RS and unstable RA degrade fatigue life and dimensional stability in critical components.

Our original contribution lies in the extensive analysis and direct comparison between experimental measurements and digital simulation outputs. this approach is rarely addressed in reviews dedicated to this alloy.

The results reveal some basic points, such as the large discrepancy (often around 20%) between experimental data and simulation predictions. This is primarily attributed to simplified phase-transformation models in finite element method (FEM). The lack of standardized protocols for measuring residual stress (RS) is another gap that needs addressing. The high computational cost of some methods that accurately record the evolution of both RS and RA is also a problem.

To bridge these gaps, the review emphasized the necessity of a hybrid digital framework. This framework should integrate combining experimental and numerical approaches for residual stress and retained austenite. Ultimately, this convergence is essential for developing of AISI 4330 components. This hybridization will provide improvements to the alloy's heat treatment methods and thus expand industrial applications.

Appendix

Table A1. The research landscape of the literature.

Researchers	Retained Austenite	Residual Stress	Mechanical Performance	Heat Treatment
Reda & Mohammad (2023)	RA increases with higher austenitizing temperature and cooling rate; max 7.7 wt%	Not explicitly quantified	Hardness decreases with increasing RA	Heat treatment at 800-1000°C; water/oil quenching
Abdulkareem & Jabbar (2017)	RA volume fraction increases with heating temperature and cooling rate; max 27.2 wt%	Residual stresses linked to RA content; compressive stresses noted	Hardness decreases with increasing RA; strength increases with cooling rate	Varied heating temperatures and quenching media
Hayama et al. (2022)	RA transforms significantly during first fatigue cycle under tensile loading	Compressive residual stress increases as RA transforms	Not detailed	In situ XRD during fatigue loading on carburized steel
Katemi & Epp (2021)	RA content varies 30-70% near surface depending on carbonitriding	High residual stresses in martensite influenced by RA fraction	Surface hardness influenced by RA content	Carbonitriding with varied carbon/nitrogen potentials
Katemi & Epp (2022)	RA decomposes during tempering; stable at lower tempering temps	Residual stresses relax during tempering and cooling	Mechanical properties affected by RA stability during tempering	In situ XRD during continuous and isothermal tempering
Katemi & Epp (2019)	RA content reduced by cryogenic treatment; thermal stabilization with tempering	Higher compressive residual stresses after tempering and cryogenic treatment	Hardness increases with tempering and cryogenic treatment	Carbonitriding followed by tempering and cryogenic treatment
Katemi et al. (2014)	RA and residual stress distributions vary with carbon/nitrogen content	High residual stresses observed; location influenced by alloying	Not detailed	Carbonitriding under varied conditions
Kuntz et al. (2024)	RA stability affected by secondary tempering; transformation-induced plasticity observed	Residual stresses relax during tempering	Fatigue and tensile properties at room and elevated temperatures	Secondary tempering of nanostructured bainite
Ooi et al. (2018)	Higher RA and compressive residual stress improve rolling contact fatigue life	Compressive residual stress mitigates crack propagation	Not detailed	Modeling and experiments on carburized steel
Prabhu et al. (2020)	Not focused on RA	Residual compressive stress depth influenced by rolling force	Surface hardness and corrosion behavior improved	Turn-assisted deep-cold-rolling
Kumar & Singh (2019)	Higher RA content increases fatigue crack growth threshold	Not detailed	Plane strain fracture toughness improved	Austempering at 250-350°C

Table A2. Chronological review of literature.

Year Range	Research Direction	Description
1970–1989	Basic studies on retained austenite and fatigue	Initial research established the relationship between retained austenite, residual stresses, and fatigue resistance in carburized steels, revealing transformation-induced plasticity effects and crack initiation and propagation under cyclic loading. Early fatigue testing and microstructure analysis highlighted the effects of retained austenite on fatigue life and mechanical performance, laying the groundwork for understanding phase transformations and residual stress impacts.
1990–1999	Heat treatment effects and microstructure optimization	Focus shifted to investigating heat treatment protocols including tempering and quenching, which affect retained austenite stability, morphology, and mechanical properties. Studies demonstrated how controlled heat treatments could optimize a multiphase microstructure containing retained austenite, bainite, and martensite to enhance strength and toughness. Techniques such as X-ray diffraction were widely adopted to quantify retained austenite and residual stresses, improving understanding of microstructural evolution.
2000–2009	Residual stress measurement and surface treatment impact	• Research expanded to detailed residual stress profiling using XRD and other methods. • The interaction between retained austenite content, residual stress states, and fatigue behavior was studied. • The transformation behavior of retained austenite during fatigue was linked
2010–2019	Advanced characterization and microstructure-property relationships	• Microstructural characterization methods (in-situ measurements and modeling approaches such as finite element simulations). • The influence of retained austenite morphology, stability, and transformation behavior on mechanical performance. • Heat treatment regimens for control retained austenite and residual stress.
2020–2024	Microstructure design and mechanistic insights on fatigue and transformation	• Nanoscale control of retained austenite morphology and stability through tailored heat treatments and alloy design. • The mechanistic links between retained austenite transformation, residual stress evolution, and fatigue resistance. • Using advanced experimental techniques and modeling. • Balancing strength, ductility, and fatigue life by managing phase transformations and residual stress anisotropy under cyclic loading for critical structural applications.

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