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ESTIMATION OF RESIDUAL STRESS OF AISI 4330 STEEL ALLOY RESULTING FROM HEAT TREATMENT PROCESSES USING NUMERICAL MODELING METHODS OF ANSYS SOFTWARE

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ABSTRACT

This investigation for the reasoning of estimating the residual stresses developed in AISI 4330 steel during the heat treatment process via ANSYS finite element software. A coupled thermo-mechanical finite element analysis in the case of a cylindrical specimen was used to model the quenching process at various thermal conditions. The two types of cooling mediums, water and air, were tested at a variety of austenitizing temperatures 650degC to 900degC. The numerical model leveraged the powerful functions in ANSYS, especially the capabilities of the program to include temperature dependence of material properties, transient thermal fields and non-linear mechanical behavior, to precisely model the interactions between thermal gradients, phase transformations and resultant stress fields.

The results show that water quenching favoring the formation of high tensile stresses at surface with a transition to compressive stresses going to the core, especially for higher austenitizing temperature. In contrast, air cooling produces much lower and more homogeneous tensile stresses in the specimen. These results point at the sensitivity of the development of residual stress to the severity of the cooling and the history of thermal. Ultimately, the study shows that ANSYS

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provides an effective and reliable virtual environment for the prediction of residual stress distributions, for the optimization of heat treatment parameters and for the reduction of the reliance on expensive and time-consuming experimental procedures.

Keywords: Finite element analysis (FEA), Quenching process, Thermo-mechanical modeling, Phase transformations, Numerical simulation.

1. INTRODUCTION

Low-alloy high-strength steels are important materials in engineering industries with variable and severe stressing requirements. AISI 4330 stands out as one of these advanced alloys, characterized by combination of mechanical properties that combine high strength, hardness, and fatigue resistance. It also possesses good heat treatment and welding amenity [1].

These properties make AISI 4330 ideal choice for engineering applications subjected to high dynamic loads and shocks, such as some aircraft structural components (wing and fuselage sections), gas turbine hubs, drilling equipment in the oil and gas sector and crankshafts and transmission gears in the heavy automotive industry [2,3].

This alloy acquires its outstanding mechanical properties through heat treatment specifically quenching. During rapid cooling, micro-structural transformations occur transforming the structure from the austenite phase at high temperatures to the hard martensite phase, ensuring the desired hardness and toughness [4].

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Fig.1: AISI 4330 application [2]

The tempering process offer major benefits to steel alloys, but it faces significant challenge: the generation of residual stresses. These stresses arise as result of the sharp thermal gradients and heterogeneous phase transformations that occur during the cooling process. The cold surface contracts rapidly while the core (inside) is still hot and expanding, generating tensile stresses at the surface. Later, as the core cools and contracts, these stresses may be reversed becoming tensile stresses in the core and compressive stresses at the surface.

Large and severe residual stresses have multiple, disastrous effects on the performance of part, including cracking during manufacturing or in service, distortion, which causes changes in geometry and design dimensions, and reduced fatigue strength, as tensile residual stresses act as a crack initiator under variable loads. Residual stresses also lead to reduced impact toughness and accelerated corrosion in some environments [5].

The engineering industry mostly relies on experimental methods to estimate and measure these stresses, such as X-ray diffraction and hole-drilling.

These experimental methods are accurate, but they are often expensive and time consuming. They provide data for only a limited number of points on the sample

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and do not provide complete three-dimensional stress distribution diagrams. These reasons are the primary motivation for the search for more efficient alternatives.

1.2.Literature Review

This research is based on theoretical and applied framework developed through careful research and extensive literature review published in peer-reviewed journals. This review is divided into three main areas which are: (1) residual stresses in metals, (2) heat treatment structure process modeling, and (3) specific research on AISI steel alloys.

1.2.1. Residual Stresses in Metals

The subject of residual stresses is broad research topic in materials science and mechanical engineering. Northwood et al. (2007) explained in a series of reviews that included a classification of residual stresses into three types: Type I (at the macro level), Type II (at the grain level), and Type III (at the atomic level). Macro stresses arise primarily due to thermal or strain gradients inhomogeneous conditions during manufacturing processes such as welding and heat treatment [7].

In the process of measuring residual stresses, experimental methods are the most accurate method and the primary criterion for verification. Rahimi et al. (2018) critically examined residual stress measurement methods, comparing the advantages and disadvantages of the most common methods, such as X-ray diffraction (XRD), hole-drilling, and neutron diffraction. The study concluded that while XRD provides high accuracy for surface measurements, methods such as hole-drilling are semi-destructive and provide data at greater depths, making them suitable for verifying simulation models [8].

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1.2.2. Modeling Heat Treatment Processes

Numerical modeling using the finite element method (FEA) has become essential tool for understanding the physics of complex heat treatment processes in recent years. The success or otherwise of these numerical models is dependent on the accurate modelling of the transformations within the material. Hang Chen et. al (2022) proposed a coupled thermo-mechanical-metallurgical model that can simulate the tempering process in carbon steel. They applied Koistinen-Marburger relation to the transformation to the martensite and for diffusional transformations, Johnson-Mehl-Avrami (JMA) equation. Their model showed a high predictability of the final microstructure as well as the level of residual stresses [9].

In a subsequent study, Jonaet et al. (2021) extended this approach to include the effect that tempering has on the residual stress relaxation, highlighting the importance of considering the temperature dependence of mechanical properties (like the elastic modulus and the yield stress) in the model to obtain accurate results. Good agreement between the model predictions and experimental measurements was noted [10].

There is wealth of published research on AISI alloys such as 4140 and 4340, but published research specifically focusing on AISI 4330 is relatively limited. Given the high similarity in chemical composition and behavior, studies on similar alloys are crucial.

1.3.Research Gap

This review demonstrates that there is important research effort in modeling heat This Review shows that there is important research effort in the modelling of heat treatment processes and residual stresses in steel alloys. However, the bulk of the studies are on other alloys (such as 4340, 4140) or for different manufacturing processes (such as welding). Specific studies on AISI 4330 are limited in time [12] and no coherent study covers a complete and validated numerical model to

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study the effect of cooling parameters on residual stress fields of this alloy using ANSYS software. Therefore, this research aims at filling up a certain blank by establishing a complete and valid numerical model for AISI 4330 during tempering focused on the effect of tempering process on residual stress fields. This gives an accurate predictive tool for this particular alloy.

1.4.Research Objective

This research is aimed to develop an accurate predictive numerical model using an advanced simulation software known as ANSYS in order to simulate the cooling process in heat treatment of the alloy material known as AISI 4330.

The model will focus on:

1. Simulating Coupling between Thermal & Mechanical Fields (Coupled Thermo-Mechanical Analysis).
2. Estimating and visualizing the residual stress fields of the material at the end of the cooling process.
3. Studying the impact of the heat transfer coefficient (cooling rate) from both the final microstructure and level of residual stresses.

This model will play a role in closing the gap between design and manufacturing, allowing engineers to virtually predict the results of heat treatment and make virtual changes to parameters (e.g., tempering temperature, type of cooling medium, etc), which will reduce the need for costly laboratory experiments and improve product quality and reliability.

2. LITERATURE REVIEW

This research is based on theoretical and applied framework developed through careful research and extensive literature review published in peer-reviewed journals. This review focuses on three main areas: (1) residual stresses in metals, (2) modeling of heat treatment processes, and (3) specific research on AISI steel alloys.

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2.1. Residual Stresses in Metals:

The subject of residual stresses is broad research topic in materials science and mechanical engineering. Northwood et al. (2007) explained in a series of reviews that included a classification of residual stresses into three types: Type I (at the macro level), Type II (at the grain level), and Type III (at the atomic level). Macro stresses arise primarily due to thermal or strain gradients inhomogeneous conditions during manufacturing processes such as welding and heat treatment [7].

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3. THEORETICAL BACKGROUND

3.1. Heat Treatment of AISI 4300-Series Alloys and Its Effect on

3.1.1. Mechanical Properties

Steel alloys in the AISI 43xx family (including AISI 4330) undergo standard heat treatment processes to achieve a combination of hardness, toughness, and fatigue resistance. The basic process is quenching and tempering.

A. Quenching:

Methodology: Heating the alloy to austenitizing temperature (usually between 830- 870 °C for AISI 4330) and holding it there for sufficient period of time to ensure complete transformation to homogeneous austenite, followed by rapid cooling in a medium such as oil or water.

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Mechanical/Microstructural Effects: The goal is to transform the microstructure into martensite a hard, brittle phase characterized by a needle-like structure. This trans-formation results in dramatic increase in hardness and tensile strength, but at the expense of toughness and impact resistance [13].

B. Tempering:

Methodology: Reheating the tempered steel to temperatures below the critical transformation (usually between 200-650 °C) for specified period of time, followed by air cooling.

Mechanical/microstructural effect: This process aims to relieve internal residual stresses and improve toughness. Unstable martensite is transformed into finer and more stable tempered martensite and carbides. Increasing the tempering temperature results in a decrease in hardness and tensile strength but considerable increase in toughness and impact resistance [1].

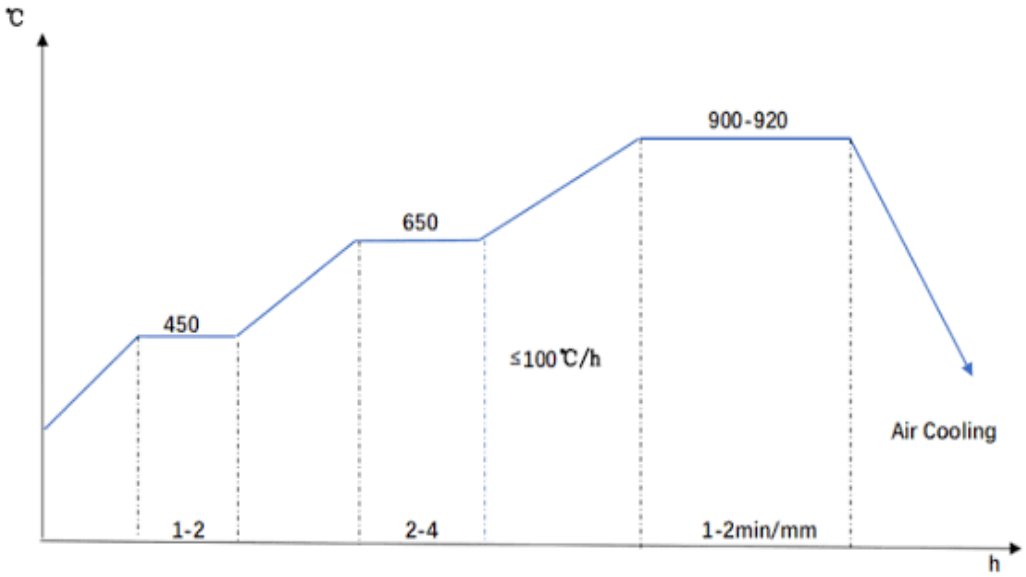


Fig. 2 : Heat Treatment Process Diagram Showing Quenching of AISI 4330 Steel

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Residual stresses in steel during rapid cooling (tempering) are generated by two factors:

1. Thermal stresses: Due to the steep temperature gradient between the surface (rapidly cooled) and the core (hot), causing inhomogeneous shrinkage.
2. Transformation stresses: This is the most important factor. The phase resulting from rapid cooling (martensite) has an atomic volume approximately 4% larger than the original phase (austenite). This inhomogeneous volume expansion is the primary driver of the high residual stresses.

3.2. Finite Element Theory (FEM)

The finite element method is numerical tool for solving complex partial differential equations governing engineering problems. The basic principle is to discretize continuous geometry (domain) into a finite number of small elements connected at points called nodes. The underlying unknown (such as displacement or temperature) is solved at these nodes, and the solution is then extrapolated within each element using shape functions [15].

The solution process consists of three basic stages.

1. Pre-processing: The geometry, material properties, element mesh, and boundary conditions are defined.
2. Processing/Solution: The global matrices (stiffness, heat capacity, etc.) are combined and the system of equations is solved:
   $[K]\{u\} = \{F\}$ (1)
   where [K] is the stiffness matrix, {u} is the displacement vector, and {F} is the load vector.
3. Post-processing: The results (stress, strain, temperature, etc.) are displayed and analyzed.

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3.3. Coupled Thermo-Mechanical Analysis

Coupled analysis should be used to simulate a process such as tempering, where mechanical stress is generated directly from a temperature gradient. This type of analysis solves the heat transfer and mechanical equations simultaneously or in close succession [15].

A. Basic Governing Equations:

Transient Heat Transfer Equation:

$$\rho C_p \frac{\partial T}{\partial t} = \nabla(k \nabla T) + Q_{gen} \quad (2)$$

where ρ is the density, $C_p$is the specific heat capacity, T is the temperature, t is the time, k is the thermal conductivity, and is any internal heat source (such as the heat of phase transition).

Equilibrium equation (In the incremental form for nonlinear analysis):

$$\nabla.\{d\alpha\} + \{db\} = 0 \quad (3)$$

where {dσ} is the incremental stress tensor, and {db} is the Incremental load vector.

Stress-strain relationship (constitutive relationship):

$$\{d\sigma\} = [D](\{d\varepsilon_{tot}\} - \{d\varepsilon_{th}\} - \{d\varepsilon_{pl}\} - \{d\varepsilon_{tr}\}) \quad (4)$$

where [D] is the elastic/plastic matrix, $\{d\varepsilon_{tot}\}$ is the total strain, $\{d\varepsilon_{th}\}$is the thermal strain, $\{d\varepsilon_{pl}\}$is the plastic strain, and $\{d\varepsilon_{tr}\}$is the transition-phase-interaction (TRIP) strain.

b. Thermal Strain: The primary driver of stresses is calculated using the equation:

$$\varepsilon_{th} = \alpha(T - T_{ref}) \quad (5)$$

where α is the coefficient of thermal expansion, and T_{ref} is the reference temperature (usually 20 °C).

Transformation-Induced Plasticity (TRIP) Strain: A very important phenomenon where plastic strain occurs even under stresses lower than the yield stress due to

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the volume change associated with the phase transformation. It is often modeled using the Leblond model [16].

3.4. Basic Properties of AISI 4330 Alloy

For the numerical model, the accuracy of the input physical properties is crucial, which have to be taken into consideration as temperature-dependence. The following table summarizes the basic properties needed for modeling, as well as their usual sources [1].

Typical chemical composition (wt.%): C: 0.28 - 0.33, Mn: 0.60 - 0.80, Si: 0.15 - 0.35, Ni: 1.65 - 2.00, Cr: 0.70 - 0.90, Mo: 0.20 - 0.30, Fe: Balance.

4. THERMO-MECHANICAL MODELING USING ANSYS

A 3D model was developed in ANSYS 2022 using Finite Element Method (FEM), integrating the transient thermal and structural analyses.

4.1. Geometric Modeling

To attain the aims of the research, a geometric model was made representing a typical test specimen often used in heat treatment studies while reducing the level of complexity and computation while maintaining the basic physical principles. The chosen model is a cylinder with dimensions of 25 mm in diameter (D) and 100 mm in height (H).

This sample was chosen because The cylinder model allows for the assumption of axial symmetry, and to Avoiding Edge Effects: A sufficient length (H = 3D) allows us to assume that the thermal and stress gradients in the center of the specimen are not significantly affected by the upper and lower edges, enabling us to analyze the results in a stable region.

The geometry was designed by space claim schematically shown in Figure 2.

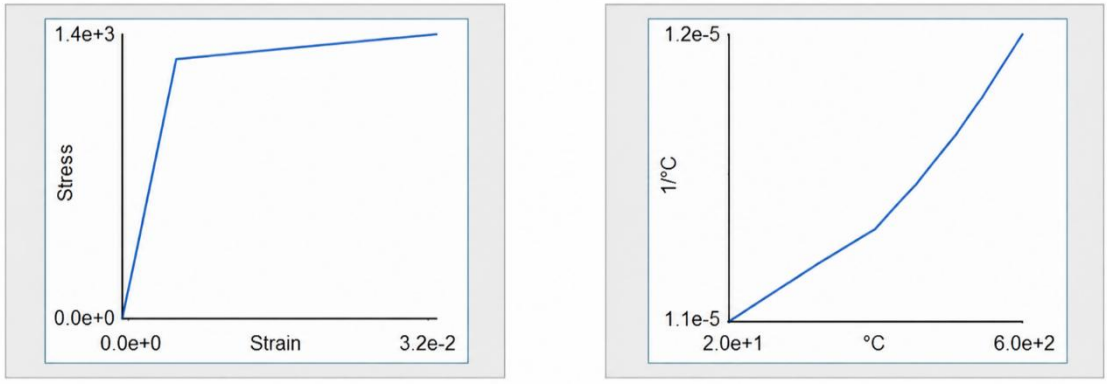
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4.2. Material Properties

A new material AISI 4430 was added to the properties of the ANSYS program, where temperature-dependent thermal and mechanical properties were entered according to standard specifications.



Bilinear Isotropic Hardening Coefficient of Thermal Expansion

Fig. 3 : Alloy steel 4330 proprieties in ANSYS

4.3. Meshing

The mesh was generated using ANSYS Meshing. Due to the expected steep temperature and stress gradients near the surface during cooling, a mapped mesh was used in the three-dimensional model, with finer sizing at the edges.

Element Type: Higher-Order Elements (PLANE223) were used (for Axisymmetric Coupled-Field Quad 8-node modeling. This element is especially used for thermo-mechanical coupled analyses and therefore has 2 degrees of freedom (motion + temperature) at each node. Higher-order PLANE223 elements were used, because they let the thermal and mechanical responses to be controlled together in a one model. This select may give a practical level of preciseness of coupled-field problems. The mesh was arranged in a planned manner. With closer elements (0.5 mm) to the surface to more closely follow the sharper thermal and

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stress variations. And with coarser elements (2mm) in the core in order to save the model controllable.

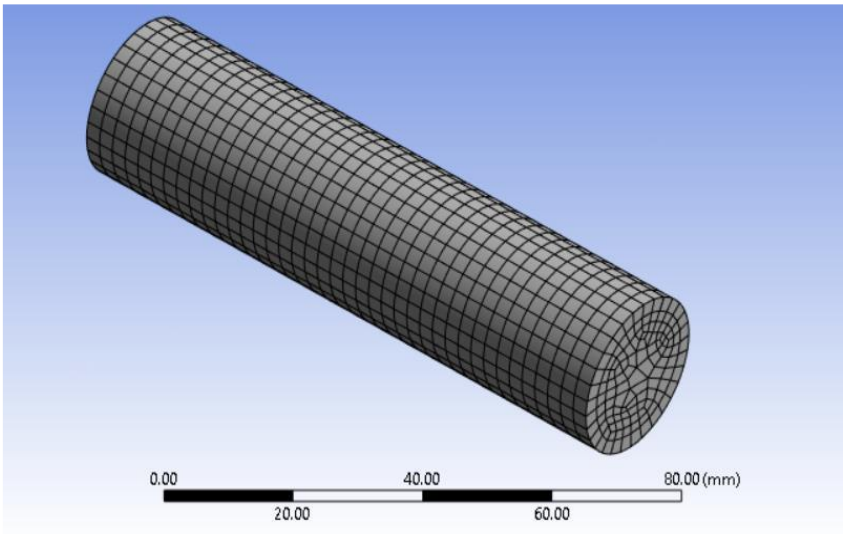


Fig. 4: Mesh of Body

A modeling of the heat treatment processes, including heating and cooling, was performed to estimate the residual stresses according to the following steps.
The figure below represents a model of the ANSYS Workbench modeling project for a case study.

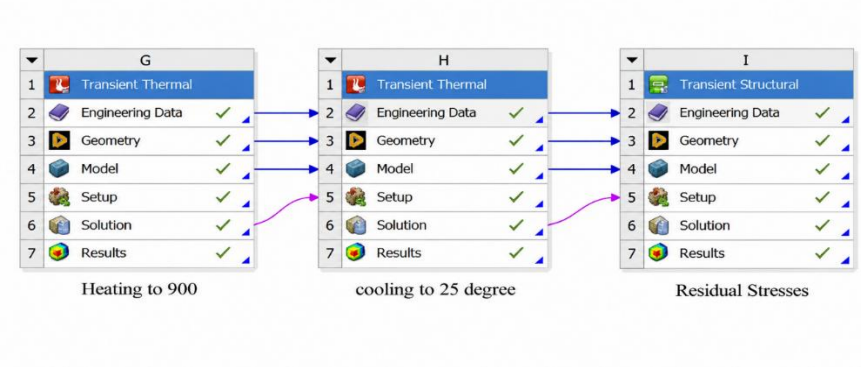


Fig. 5: Flow chart of work

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4.4 .Boundary and Initial Conditions

4.4.1 Thermal Boundary Conditions

Convection Condition: A convection condition was applied to all surfaces exposed to the cooling medium. The heat transfer coefficient (HTC) was defined not as a constant value, but rather as a function of surface temperature (temperature-dependent) to increase simulation accuracy. HTC values were derived from a published experimental study of the cooling of AISI 4140 steel in oil [3], assuming similar behavior to AISI 4330.

4.4.2. Heating Phase and Initial Condition

The specimen was heated from room temperature to the target temperature (650–900°C) at a constant rate of 100°C per hour to avoid thermal shock and ensure uniform temperature distribution. After reaching the target temperature, the specimen was held for 60 minutes to achieve complete automatization. At time t = 0, the entire specimen was assumed to be at a uniform quenching temperature with zero initial stress.

4.4.3 Mechanical Boundary Conditions:

To avoid rigid body motion without restricting the natural thermal shrinkage of the sample, the following conditions were applied to the axial model, constraint was applied to the axis of symmetry: preventing movement in the radial direction (UX = 0), and constraint was applied to a single point at the base: preventing movement in the axial direction (UY = 0) at the center point of the base. This prevents rigid motion without applying excessive constraints that would affect the stress distribution.

4.4.4 Initial Condition

The entire sample was assumed to be at a uniform temperature at time t = 0, which is the quenching temperature of 850 °C. The sample was also assumed to be stress-free initially.

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4.5. Simulation Settings

The heat treatment simulation was based on unsteady-state thermal analysis. The simulation was performed using the ANSYS Transient Thermal coupled with Static Structural solver.

Analysis Type: Transient analysis with variable time steps automatically controlled by the software based on the rate of convergence of the solution. A total simulation time of 1000 seconds was used to ensure the sample reached ambient temperature (40 °C).

Time Step Control: Auto Time Stepping was used with an initial time step of 0.1 seconds and a minimum time step of 10 seconds. This setting ensures that the fast dynamics at the start of cooling are captured while increasing efficiency when cooling rates slow down.

Nonlinear Algorithm: Given the dependence of material properties on temperature and strain state, and the presence of plastic behavior, the Newton-Raphson algorithm was used to solve the nonlinear equations.

Convergence Criteria: Strict convergence criteria were adopted for forces and displacements (criterion = 0.5%) to ensure the accuracy of the results.

Transient thermal simulation: it was performed by thermal source with Goldak bi-elliptical model, heat transfer h=15 w/cm2, time between layers is 60 second. A tempertaure900°C was applied at each time step, the time step is 0.01 second And then the thermal load was applied as an external load at each step.

Transient structural simulation: In addition to applying the thermal convectionload, the plates were fixed at both sides to implement the structural

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solution, low pressure was also applied to simulate tank conditions. We note that the residual stress is maximum at the edges.

4.6. ANSYS Analysis to Estimate Residual Stresses in AISI 4330 Steel under Water Cooling conditions (quenching treatment)

In order to estimate the residual stress using the ANSYS software, we conducted the necessary analysis, taking into account all the points we mentioned previously. We repeated the process at six points ranging between 650 and 900°C. After stabilizing the temperature for a 60 minute at the target temperature, we cooled the sample to a 40°C using water. The analysis results were as stated in Table 1. The figure 6-a shows the analysis results for a sample at the temperature700°C. According to the results, the residual stress at the end of the sample is large and gradually decreases until reaching the center of the sample due to the sample being restricted from both ends. The figure 6-b also shows that the stress decreases from the surface of the sample towards the insideuntil reaching the center and may take a compressive form.

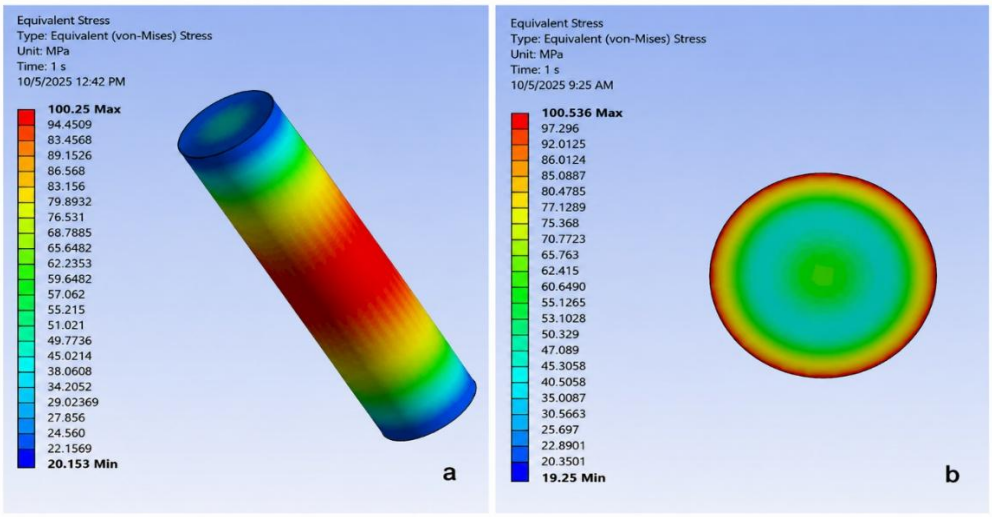


Fig. 4 : Residual Stress Distribution in AISI 4330 Steel at 700°C with water Cooling (ANSYS Simulation)

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4.7. ANSYS Analysis to Estimate Residual Stresses in AISI 4330 Steel under air Cooling conditions (quenching treatment)

To study the effect of rapid and slow cooling on residual stresses, all six samples were reprocessed under the same heating conditions and holding time, but here the cooling was done by air. The table 2 shows the results of all samples analyzed as mentioned above. The figure 7 shows the results of analyzing one of the samples at processing temperature 750°C. The results indicate that the stresses were generally lower compared to the water-cooled samples, and that the stresses at the edges and surface of the sample were larger compared to the center of the sample, respectively.

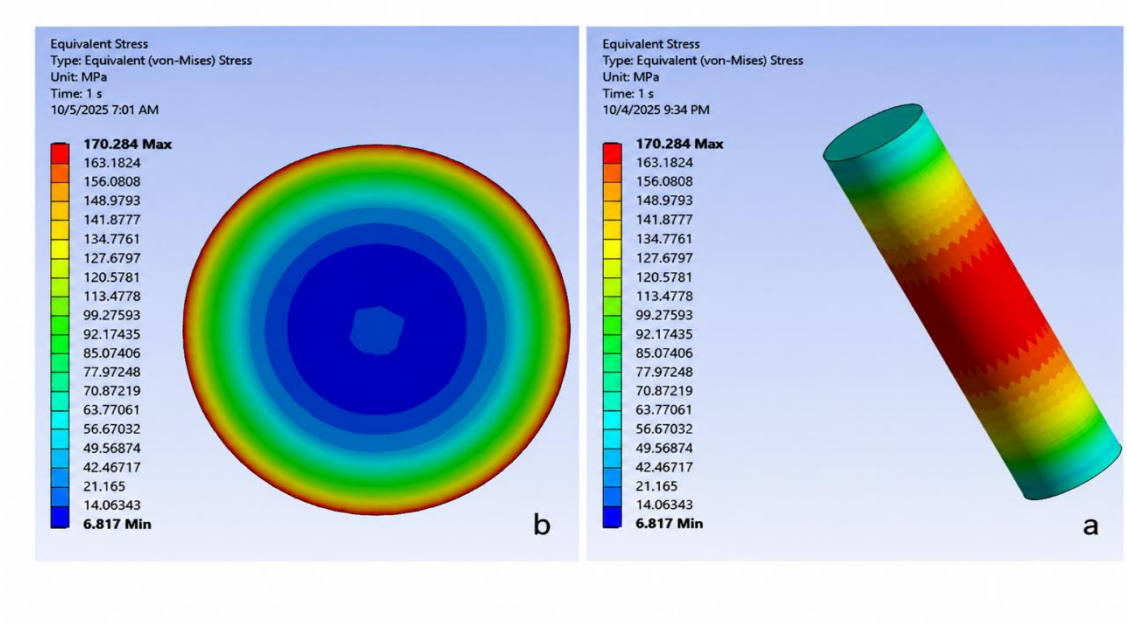


Fig. 5 : Residual Stress Distribution in AISI 4330 Steel at 750°C with air Cooling (ANSYS Simulation)

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5. RESULTS AND DISCUSSION

Certainly, as is clear from the results of the two tables 1,2, the cooling method plays the most prominent role in finding and distributing residual stresses. Water quenching (Rapid Cooling) generates high residual stresses. The stress profile evolves with increasing temperature, starting with tension throughout the cross-section and transitioning to a classic profile of high surface tension and core compression at higher temperatures. Air cooling (Slow Cooling) generally results in much lower residual stresses. The stress profile is more complex and is significantly influenced by specific phase transformations occurring at different temperatures.

Table 1: The Residual Stresses in AISI 4330 Steel under water-cooling

Quenching temperature (°C)	Cooling medium	Holding Time (min)	RS calculated After quenching (Mpa)	Interpretation of results
650	Water	60	137 (surface) → 43 (center)	At low temperature, the thermal gradient during quenching is moderate. Transformation to martensite occurs, but with a lower rate and completeness. This results in tensile stresses throughout the cross-section, but their magnitude is relatively low due to the smaller differential in contraction and phase transformation between the surface and core.
700	Water	60	170 (surface) → 6.8 (center)	As the austenitizing temperature increases, the thermal gradient becomes steeper. The surface contracts severely while the core is still hot and expanding, generating higher tensile stresses at the surface. The core responds with lower tensile stresses to maintain equilibrium.
750	Water	60	191 (surface) → 2 (center)	The thermal gradient becomes more pronounced. The volumetric change from the martensitic transformation at the surface begins to strongly oppose the core, pushing the core stress towards a neutral state as a transitional region.
800	Water	60	232 (surface) → -12 (center)	This is a critical transition point. Rapid cooling from this high temperature causes a swift and complete martensitic transformation at the surface

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				with significant volumetric expansion. This expansion "forges" the still-hot and soft core, plastically deforming it. When the core later cools and contracts, it is constrained by the already hard surface, resulting in compressive stresses (compression) in the core.
850	Water	60	253 (surface) → -34 (center)	The previous mechanism intensifies. The phase transformation at the surface is more complete, and the volumetric expansion is greater, increasing both the surface tensile and core compressive stresses.
900	Water	60	278 (surface) → -66 (center)	Quenching from the highest temperature creates the maximum thermal gradient and the highest rate of martensitic transformation. This results in the highest surface tensile stresses and the highest core compressive stresses. This state carries the highest risk of **quench cracking** if the surface tensile stress exceeds the ultimate tensile strength of the material

Table 2: The Residual Stresses in AISI 4330 Steel under air-cooling

Quenching temperature (°C)	**Cooling medium**	**Holding Time (min)**	**RS calculated After quenching (Mpa)**	**Interpretation of results**
650	Air	60	56 (surface) → 0.9 (center)	The slow cooling rate minimizes thermal gradients. Phase transformations occur slowly and may not result in full martensite, likely forming a mixture of ferrite, pearlite, and/or bainite. This allows stresses to relieve through plasticity, resulting in a very low, near-neutral stress state.
700	Air	60	67 (surface) → 11 (center)	Stresses remain low but show a slight increase. The final microstructure is stronger than at 650°C, allowing it to sustain slightly higher residual stresses from the mild differential contraction during cooling.
750	Air	60	100 (surface) → 20 (center)	A noticeable jump in surface stress. Cooling from this temperature likely results in a higher proportion of stronger phases like bainite. The increased strength of this microstructure prevents stress relief through plastic flow, locking in higher thermal stresses.
900	Air	60	233 (surface) → 43 (center)	The highest temperature results in the strongest air-cooled microstructure and highest thermal gradient in the cooling process. This combination gives the greatest residual stresses for air cooling but not more than one half that obtained with water quenching.

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Finally, we summarize the numerical results in the points below:

1) Cooling Rate is Paramount: It is the nature of the cooling medium (water vs. air), rather than the actual quenching temperature, that has a more dramatic effect on the magnitude of the stress. Water produced stresses over 4 times of air pressure.
2) Quenching Temperature Controls Stress Profile In rapid quenching, higher temperatures are required to attain the classic and desirable compressive core stresses but have the penalty of very high surface tensile stresses.
3) Microstructural Strength Locks in Stresses The final stress state is not a function simply of thermal gradients, but is critically dependent on the strength of the formed phases. Stronger Microstructures (Martensite with water stronger bainite with air) Higher locked-in residual stresses
4) Practical Instructions to Heat Treatment:
   - ✓ In order to get high hardness and favorable compressive core stress, it requires water quenching from high temperature (such as 850 to 900 degrees centigrade). However, this must always be followed with tempering to relieve the dangerous surface tensile stresses to ensure against quench cracking.
   - ✓ Air cooling is a much safer process and there is very little risk of distortion or cracking and is suitable for situations where high hardness is not the most important consideration. The resulting tensile stresses are usually low and often acceptable without additional treatment.

6.RECOMMENDATIONS FOR REDUCING RESIDUAL STRESSES IN AISI 4330 STEEL

Based on previous studies, a few approaches can be useful in achieving the reduction of the residual stresses in AISI 4330 steel. These ways do not ensure perfect results. Depending on the situation they may make practical improvements. Tempering stayed a key step. Tempering about 380-400°C is often

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helpful to reduce residual stresses without material loss of suitable mechanical properties.

The working above 500 °C , however, may lead to clear softening [14]. Another factor to be considered is cooling rate. Slow cooling such as air cooling in final stages may help to limit thermal gradients and reduce stress build-up [16]. Some post treatment methodologies are also possible. For example, vibratory stress relief (VSR) may reduce internal stresses. Without it affect considerably on surface hardness [17].

Thermochemical treatments such as nitrocarburizing with oxidation may introduce compressive stresses at the surface. This could be helpful for fatigue performance [12]. It is also of value to study the first heat treatment parameters. Adjustment of austenitizing temperature and soaking time may be useful to improve the grain structure. It also minimizes the possibility of high residual stresses [4].

A stress relieving treatment about 650°C for up to two hours. It is often informed as useful option for dropping in internal stresses. While it is maintaining a stable organization [5].

Finally, numerical modeling can be used to investigate different process conditions. Before it is running physical examinations. While it may not cover all of the points it may still give a rough idea of how changes in parameters might affect the residual stresses [11].

7. CONCLUSION

This research is able to prove successfully the use of numerical modeling to predict the residual stresses in AISI 4330 steel. ANSYS software was an integral part of this research, as it allowed for a thermo-mechanical analysis which simulates the combination of temperature gradients and phase transformations.

Its ability to model the heat treatments and give 3-dimensional analyses is a good improvement over the experimental methods. Simulations revealed that water

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quenching from high temperatures produces high surface tensile stresses, then there is need for tempering again in contrast the air quenching provides a low-stress mode.

Ultimately, this model, based on ANSYS, offers a cost-effective tool, states away from physical experiments, gives reduced the risk from cracking and deformation and boosts the reliability of critical elements within engineering use.

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