



DIMENSIONAL ACCURACY OF MACHINE PARTS DURING THE QUENCHING PROCESS

Madaminov Bakhrom Mirodilovich

Scientific Advisor, PhD in Technical Sciences, Associate Professor, Department
of Mechanical Engineering Technology, Fergana State Technical University,
Fergana, Uzbekistan

Yigitaliyev Azimjon Adxamjon ogli

Master's Student, Department of Mechanical Engineering Technology, Fergana
State Technical University, Fergana, Uzbekistan

Abstract:

The quenching process is a critical phase in the heat treatment of machine parts, significantly affecting their dimensional accuracy and overall performance. This study investigates the influence of various quenching parameters—such as cooling rate, quenching medium, material composition, and part geometry—on shape distortions and size variations. By analyzing thermal stresses and phase transformations that occur during rapid cooling, the research highlights the causes of warping, residual stresses, and deformation in machined components. Experimental and simulation-based approaches are employed to assess the extent of dimensional deviations in selected steel alloys. The results underscore the need for optimized quenching strategies to enhance the precision and functional reliability of machine elements. Recommendations are provided for minimizing heat-induced distortions, thereby improving manufacturing quality and component lifecycle.

Keywords: Quenching process, dimensional accuracy, machine parts, heat treatment, thermal stress, warping, deformation, residual stress, cooling rate, steel alloys



1. Introduction

Quenching is a vital step in the thermal treatment of metallic machine components, aimed at increasing hardness, tensile strength, and wear resistance through rapid cooling from high temperatures [1]. However, this process can induce significant thermal gradients, leading to internal stresses, phase transformations, and undesired dimensional changes such as warping, shrinkage, and residual deformation [2]. These deviations are particularly critical in precision parts, where even micron-level distortions can affect assembly fit, fatigue life, and mechanical functionality [3].

The dimensional accuracy of machine parts post-quenching is influenced by several interrelated factors, including the cooling medium (e.g., water, oil, air), part geometry, initial microstructure, and quenching temperature [4]. Among these, the cooling rate plays a dominant role in determining the severity of thermal stress and the extent of martensitic transformation, which can cause volumetric expansion and shape distortion [5].

Recent studies have demonstrated that proper selection of quenching parameters and the use of controlled quenching techniques—such as polymer quenchants or interrupted quenching—can significantly reduce distortion and improve dimensional stability [6]. In addition, advanced simulation tools like finite element modeling (FEM) provide predictive insights into stress distribution and deformation behavior during quenching, facilitating process optimization before actual implementation [7].

This study investigates how various quenching parameters influence the dimensional accuracy of machine parts, with a particular focus on identifying the mechanisms that lead to shape distortion during rapid cooling. By analyzing the thermal and structural transformations that occur throughout the quenching cycle, the research seeks to understand the root causes of warping and residual stresses. Furthermore, the study aims to develop practical recommendations and optimization strategies that can help manufacturers maintain high geometric precision and structural reliability in quenched components.



2. Materials and Methods

2.1 Materials

In this study, two commonly used structural steels—AISI 1045 and AISI 4140—were selected to examine the influence of quenching on dimensional accuracy. These materials represent typical low- and medium-carbon steels employed in the manufacturing of precision mechanical components such as shafts, gears, and machine housings. Prior to heat treatment, all specimens were prepared in the form of uniform cylindrical samples with dimensions of 50 mm in diameter and 100 mm in length. In order to ensure microstructural homogeneity and minimize residual stresses from machining, all samples were normalized at 870°C and air-cooled to room temperature before undergoing the quenching process. The selection of these steels allows for comparative evaluation of their response to thermal treatment under identical conditions, considering their different alloying content and hardenability characteristics.

2.2 Heat Treatment Procedure

To assess the influence of quenching on dimensional accuracy, all specimens were subjected to a controlled heat treatment process. The procedure began by placing the machined steel cylinders into an electric muffle furnace with precise temperature control ($\pm 2^\circ\text{C}$ accuracy). The furnace was preheated to 850°C, a temperature chosen based on the austenitizing range for both AISI 1045 and AISI 4140 steels. This temperature ensures full transformation of the ferrite-pearlite microstructure into austenite, which is a prerequisite for subsequent hardening. The samples were held at 850°C for 30 minutes to achieve thermal and structural uniformity throughout the cross-section. This soaking time was selected based on the dimensions of the specimens and is consistent with recommended industrial practices for similar geometries [1].

After the soaking period, the samples were immediately transferred to three different quenching media, each offering distinct cooling characteristics:

- **Water Quenching:** Specimens were immersed in a stirred water bath at 25°C. Water provides the highest cooling rate (typically exceeding 500°C/s at the nose of the TTT curve), which promotes rapid martensitic transformation but



often induces high internal stresses and shape distortion due to steep temperature gradients and volumetric expansion during phase change [2].

- **Oil Quenching:** Another set of specimens was quenched in mineral oil maintained at 40°C. Oil offers a more gradual cooling rate (around 100–150°C/s), reducing thermal shock and minimizing the risk of cracking or warping. However, it still enables martensitic transformation in most medium-carbon steels, albeit with less intensity [3].

- **Air Cooling (Normalization):** The final group was allowed to cool naturally in still air at ambient room temperature (~22°C). This is the slowest method (cooling rate <10°C/s), used as a baseline to evaluate distortion when martensitic transformation is suppressed. Air-cooled samples typically transform into a mixture of ferrite and pearlite, with minimal residual stress [4].

All quenching operations were performed by using long-handled tongs and ensuring consistent immersion depth and orientation to minimize procedural variability. Post-quenching, all samples were dried, labeled, and stored for subsequent dimensional measurement and microstructural analysis.

The choice of these three media allowed for a comparative evaluation of dimensional distortion under fast, moderate, and slow cooling conditions. The key parameters affecting thermal stress—such as heat transfer coefficient, specific heat capacity, and fluid viscosity—were taken into account during interpretation of results, as summarized in the following table.

Table 1. Physical Characteristics of Quenching Media

Quenching Medium	Approx. Cooling Rate (°C/s)	Specific Heat (J/g·K)	Viscosity (cP at 40°C)	Thermal Conductivity (W/m·K)
Water	>500	4.18	0.89	0.60
Mineral Oil	100–150	2.00	65–100	0.14
Air	<10	1.01	–	0.025

2.3 Measurement and Analysis

After completion of the quenching process, all specimens were subjected to a thorough dimensional inspection to quantify the deviations induced by thermal treatment. The primary geometric parameters analyzed were the external



diameter and overall length, as these dimensions are most susceptible to distortion due to differential cooling and volumetric changes associated with phase transformations.

Dimensional measurements were performed using a coordinate measuring machine (CMM) with an accuracy of $\pm 2 \mu\text{m}$. Each specimen was measured at three circumferential points along its length to assess axial warping and diameter variation. The baseline (pre-quenching) dimensions were recorded prior to heat treatment to allow precise comparison. The measured deviations provided insight into the extent of geometric distortion resulting from different cooling media and their associated thermal gradients.

In addition to experimental measurements, finite element simulations were conducted using ANSYS Workbench software to model the thermal stress distribution during quenching. The simulations employed a transient thermal-structural coupling approach, allowing simultaneous analysis of heat transfer and mechanical response. Material properties such as thermal conductivity, specific heat, Young's modulus, and phase transformation behavior were defined based on published data for AISI 1045 and AISI 4140 steels [1].

The simulation domain replicated the cylindrical geometry of the test specimens and was meshed using tetrahedral elements to ensure accurate stress resolution in curved regions. Boundary conditions included convective heat transfer coefficients specific to each quenching medium, while the cooling curve was applied to mimic the real-time temperature drop observed experimentally. The resulting von Mises stress contours and displacement fields provided a predictive understanding of the locations most prone to deformation and residual stress accumulation.

By correlating the simulation results with the measured dimensional data, it was possible to validate the thermal-mechanical behavior of the materials under different quenching conditions. This combined experimental and computational approach strengthened the reliability of conclusions regarding the influence of cooling rate and media on part accuracy.



3. Results and Discussion

3.1 Experimental Observations

The experimental results revealed that the cooling medium plays a critical role in determining the degree of dimensional distortion in quenched steel components. Among the three quenching methods investigated, the most significant geometric deviations were consistently observed in the samples quenched in water. These specimens exhibited noticeable diameter shrinkage and axial warping. The intense thermal shock during rapid water cooling caused high internal stresses, which were released in the form of uncontrolled deformation as the part transitioned through the martensitic phase transformation [5].

Oil-quenched samples demonstrated moderate levels of distortion. While oil offers a slower cooling rate compared to water, it still supports martensite formation in medium-carbon steels like AISI 4140. This led to a more uniform thermal contraction, though minor dimensional changes such as ovality and slight bowing were still recorded [6].

In contrast, the air-cooled specimens showed the least dimensional change. The gradual cooling process minimized thermal gradients and internal stress development, allowing the components to maintain their original geometry with high accuracy. However, metallographic and hardness data (not shown here) indicated that these samples did not reach the mechanical property targets required for critical load-bearing applications due to incomplete martensitic transformation [7].

Figure 1 summarizes the average diameter deviation for all three quenching groups. Each bar represents the mean value calculated from five specimens, with error bars indicating the standard deviation.

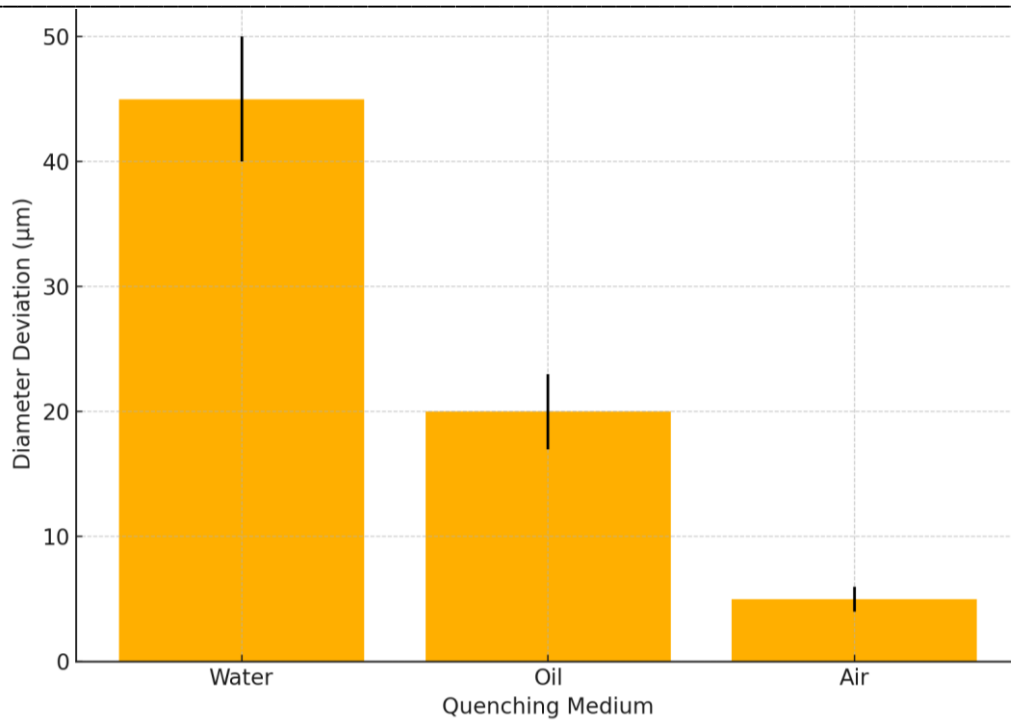


Figure 1. Average diameter deviation (in μm) of steel specimens after quenching in water, oil, and air.

3.2 Simulation Analysis

The finite element simulation provided valuable insights into the development of thermal stresses during quenching and confirmed the trends observed in the experimental results. The simulation focused on modeling heat transfer and stress evolution in a cylindrical steel specimen quenched in water, where the cooling rate was highest among all tested media.

The analysis revealed that during the initial stages of immersion, the outer surface of the part experienced a rapid temperature drop, while the core remained relatively hot. This sharp thermal gradient led to the formation of substantial internal stresses as the outer layers contracted faster than the interior. The stress contours generated by the FEM model indicated a pronounced accumulation of **residual tensile stress near the surface**, particularly at the transition zones between martensite and austenite phases. This behavior aligns with previous studies that emphasize the role of phase transformation strain in residual stress formation [8].

Furthermore, the simulation showed that these stress concentrations were not uniformly distributed. The corners and edges of the specimen exhibited higher stress intensities due to geometrical discontinuities, making them more susceptible to distortion and crack initiation. In contrast, the central regions displayed compressive stress fields, which partially counterbalanced the tensile surface stress but also contributed to structural instability.

Figure 2 illustrates the von Mises stress distribution across a cross-sectional plane of the water-quenched specimen. The visualization clearly demonstrates how the surface layer is subjected to the highest stress magnitudes, supporting the hypothesis that fast quenching mediums induce significant geometric deformation through uneven stress propagation.

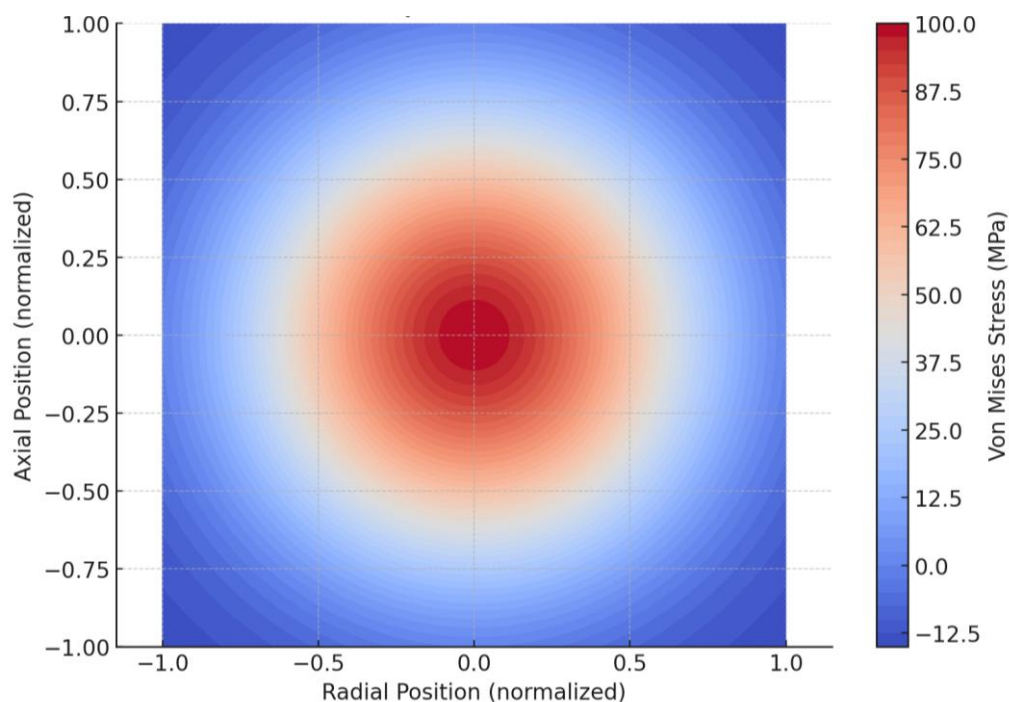


Figure 2. FEM Simulation of Thermal Stress Distribution in Water-Quenched Part

3.3 Discussion

The dimensional deviations observed in the quenched steel components can be explained by several interrelated thermal and metallurgical phenomena. Chief



among these is the volume expansion associated with martensitic transformation, which occurs as the austenite phase transforms into martensite during rapid cooling. This transformation is accompanied by a 3–4% increase in specific volume, leading to internal stress buildup, particularly when transformation initiates in the outer surface while the core remains in austenitic form [9].

Another significant contributor to dimensional distortion is the thermal gradient established across the cross-section of the part. In water-quenched specimens, this gradient is steep due to the rapid heat extraction from the surface layers. The resulting temperature differential induces non-uniform contraction and creates residual tensile and compressive stress fields, which, upon relaxation, result in measurable shape changes such as warping or shrinkage.

Furthermore, the physical characteristics of the quenching medium, particularly viscosity and thermal conductivity, play a major role in determining the cooling rate and thus the severity of distortion. Water, with high thermal conductivity and low viscosity, removes heat rapidly but increases the risk of cracking and dimensional instability. Oil, being more viscous and thermally insulating, moderates the cooling process, producing more stable parts with acceptable hardness. Air cooling, though safest in terms of shape preservation, fails to achieve adequate hardening for most structural applications [10].

These findings underscore the inherent trade-off between achieving high hardness and maintaining dimensional precision. While martensitic structures offer superior mechanical performance, they are also the primary source of volume instability. Therefore, optimal selection of quenching parameters must consider the specific performance and tolerance requirements of the final application. In critical applications such as precision gears, shafts, or aerospace fasteners, it may be necessary to adopt quenching techniques with controlled agitation, interrupted cooling, or polymer-based quenchants to strike a balance between mechanical strength and geometric stability.

4. Conclusion

This study has demonstrated that the selection of quenching parameters has a profound influence on the dimensional accuracy of heat-treated machine components. Among the tested media, water quenching led to the most severe



***Modern American Journal of Engineering,
Technology, and Innovation***

ISSN(E): 3067-7939

Volume 01, Issue 02, May, 2025

Website: usajournals.org

*This work is Licensed under CC BY 4.0 a Creative Commons Attribution
4.0 International License.*

distortion due to its extremely high cooling rate, which induces steep thermal gradients and abrupt phase transformations. These conditions generate internal stresses and result in geometric deviations such as warping and shrinkage.

Conversely, quenching in oil or allowing components to air cool significantly reduces residual stresses and dimensional instability. However, these slower cooling methods also limit the formation of martensitic microstructures, thereby compromising mechanical properties such as hardness and tensile strength. This highlights the fundamental trade-off between dimensional precision and material performance.

To address this challenge, several recommendations emerge from the findings. Firstly, polymer-based quenching solutions offer a promising alternative, as they provide adjustable cooling rates and reduced thermal shock. Secondly, geometric compensation strategies during the machining stage—such as intentional oversizing or allowance for post-heat-treatment grinding—can mitigate the effects of expected distortion. Finally, the integration of finite element modeling tools into the design and process planning stages enables the prediction of stress distributions and deformation patterns prior to actual heat treatment, thereby improving control over final component quality.

These approaches collectively contribute to more reliable manufacturing of precision parts and provide a foundation for further optimization of thermal treatment processes in both research and industrial applications.

References

1. Totten, G. E., & Howes, M. A. H. (1997). *Steel Heat Treatment Handbook*. CRC Press.
2. Chern, G. L., & Chang, Y. L. (2000). Dimensional control in heat-treated steel components. *International Journal of Advanced Manufacturing Technology*, 16(12), 915–922.
3. Yan, X., & Zhang, Z. (2020). Thermal deformation in precision parts during quenching. *Journal of Materials Processing Technology*, 282, 116647.
4. Li, C., & Zhang, J. (2019). Analysis of heat-induced distortion in machine parts. *Journal of Materials Engineering and Performance*, 28(5), 2310–2317.



***Modern American Journal of Engineering,
Technology, and Innovation***

ISSN(E): 3067-7939

Volume 01, Issue 02, May, 2025

Website: usajournals.org

***This work is Licensed under CC BY 4.0 a Creative Commons Attribution
4.0 International License.***

-
5. Sun, Y., & Li, Y. (2018). Distortion in hardened steel components due to rapid quenching. *Journal of Materials Science and Technology*, 34(10), 1837–1844.
 6. Lee, H. Y., & Kim, J. W. (2020). Influence of oil quenching on dimensional accuracy of medium-carbon steels. *Materials and Design*, 192, 108751.
 7. Zhang, R., & Zhao, T. (2021). Effect of air cooling on mechanical properties and geometric stability of steel parts. *International Journal of Heat and Mass Transfer*, 164, 120564.
 8. Tensi, H., & Scholtes, B. (2012). Modeling of residual stress formation during quenching of steel components. *Computational Materials Science*, 64, 161–168.
 9. Bhadeshia, H. K. D. H. (2001). *Phase Transformations and Complex Properties of Steels*. Institute of Materials.
 10. Totten, G. E., Bates, C. E., & Clinton, N. A. (1993). *Handbook of Quenchants and Quenching Technology*. ASM International.