

Effect of heat treatment modes on the geometric stability of metal structural elements

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Received: 22 January 2026 / Received in revised form: 25 March 2026 / Accepted: 18 May 2026

Abstract:

The present study examined the influence of various heat treatment modes on the geometric stability of metal elements made of St3, 20Kh, 09G2S, and St45 steels with thicknesses ranging from 10 to 50 mm and lengths of 400–500 mm. Samples were heated to 750, 800, 850, 900, and 950 °C with holding times of 30, 60, and 90 min, followed by cooling in water, oil, air, or in the furnace, under three fastening conditions: no fastening, rigid fastening, and flexible fastening. The results showed that an increasing heating temperature intensifies grain growth and phase transformations, leading to volume changes and local geometric distortions. Rapid cooling, especially water quenching, generated high internal stresses, causing bending and warping; in loosely fixed St45 samples with a thickness of 40 mm, residual deformation reached 2.4 mm. Annealing resulted in the lowest deformation values due to effective stress relaxation, whereas normalization and ageing exhibited intermediate values. Rigid fastening reduced visible deformation to approximately 1.3 mm but contributed to the accumulation of internal stresses, whereas flexible fastening proved most effective, limiting deformation to about 0.9 mm by compensating for thermal expansion. Alloyed steels demonstrated a lower tendency toward thermal deformation than carbon steels, and massive elements with complex geometries showed increased susceptibility to local overheating and distortion. These findings are of practical importance for optimizing heat treatment parameters, selecting appropriate cooling and fastening methods, and improving the geometric accuracy and reliability of metal structures in industrial production, particularly for enterprises in Kyrgyzstan and China.

Keywords : Modelling ; Phase transformations ; Thermal stresses ; Deformations ; Alloy steels; Fastening.

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<https://doi.org/10.70974/mat10126193>

1. Introduction

Metal structures are widely used in construction, mechanical engineering, and other industries in which the reliability and dimensional precision of structural elements are crucial. Heat treatment is one of the main methods of improving the mechanical properties of metals; its parameters determine changes in the configuration and shape stability of parts. During heating and cooling, phase transformations and thermal stresses occur, leading to deformations that can negatively affect the performance of structures [1]. In Kyrgyzstan, in particular in the laboratories of Osh Technological University, and in industrial enterprises in China, differences in heat treatment modes and their effects on the geometry of metal elements have been studied. The analysis of these factors makes it possible to identify the features of thermal regimes in different regions and to optimise technologies so as to reduce deformations and increase the durability of structures.

To ensure terminological consistency, the key terms used in this study are defined as follows. *Deformation* is the total, quantifiable change in a material's dimensions or shape caused by mechanical and thermal forces. *Distortion* is defined as non-uniform deformation that results in deviation from the intended geometry, whereas *warping* is a particular form of distortion characterised by bending brought on by uneven thermal expansion or cooling. The primary term used in this study is deformation, with distortion and warping employed more specifically to describe particular manifestations of non-uniform shape change.

Accurate prediction and effective minimisation of deformations under various technological conditions remain a complex and pressing problem in the study of how heat treatment modes influence the configuration of metal structures. Krbata *et al.* [2] investigated in detail the changes in the microstructure of steel as a function of the heating temperature regime, using metallographic analysis and mechanical testing of samples. They showed that when critical temperatures are exceeded, grain-boundary processes accelerate, leading to grain growth and a decrease in the plasticity of the material. These results are important because structural changes determine the ability of elements to maintain their original configuration. Bastola *et al.* [3] focused on the cooling rate as a key factor governing the formation of residual stresses in the metal. Experiments involving quenching in air, oil, and water revealed that rapid cooling media contribute to the occurrence of uneven deformations. These findings helped to clarify the mechanisms of warping and cracking during intensive processing modes.

Li *et al.* [4] conducted a comparative study of carbon and alloy steels using thermomechanical analysis methods. They showed that the presence of chromium and nickel significantly increases resistance to deformation owing to the stabilisation of the structure under thermal stress. These results are particularly valuable for selecting materials that undergo complex processing at high temperatures. Zhang *et al.* [5] examined the in-

fluence of the geometry and thickness of metal elements on the distribution of temperature fields during heat treatment. Using numerical modelling, they found that parts with complex shapes and variable cross-sections are more susceptible to local distortions, underlining the need to account for design features at the design stage of the technological process. Qureshi *et al.* [6] simulated phase transformations in steel and established the relationship between the selected heat treatment modes and product configuration changes. Their study confirmed that even minor deviations from optimal parameters can lead to significant shape changes, thereby expanding the understanding of the relationship between phase transformations and geometric stability.

Taler *et al.* [7] analysed the role of the methods used to fix products in the furnace during processing. Their experiments showed that rigid fastening of parts reduces the likelihood of movement and bending during heating but simultaneously increases the risk of residual-stress accumulation after cooling, indicating the need to select optimal fastening methods. Tabatabaieian *et al.* [8] considered the effect of annealing modes on residual stresses in metals, demonstrating that a properly selected mode reduces the level of internal stresses and increases dimensional accuracy, making annealing an effective method for correcting deformations. Aziz *et al.* [9] investigated the water-quenching process and found that sudden cooling increases the risk of warping owing to an uneven temperature distribution across the section of the part, confirming the need for careful application of quenching in massive structures.

Despite the wide range of studies conducted, data remain scarce on the influence of regional climatic features and production conditions, especially in countries with differing technologies and resources, such as Kyrgyzstan and China. This highlights the need for further empirical research aimed at adapting and optimising heat treatment modes to the specifics of particular regions and enterprises. The novelty of this study lies in the integrated quantitative analysis of deformation behaviour under the combined influence of heating temperature (750–950°C), cooling medium (water, oil, air, furnace), and fastening conditions (free, rigid, flexible), which have not been jointly examined in previous research. Additionally, by combining SEM, EBSD, and XRD analyses, the study introduces a microstructural–mechanical correlation to explain deformation mechanisms, specifically the role of phase transformations and crystallographic features. This approach offers a more thorough understanding of the variables influencing geometric stability and enables the identification of deformation thresholds.

The purpose of the study was to determine how different heat treatment modes affect the geometric stability and deformation of metal structural elements. The objectives were (i) to examine the changes in microstructure and thermal stresses under various heating and cooling conditions, (ii) to assess the effect of material composition and element geometry on the distribution of internal stresses, and (iii) to analyse the impact of fastening conditions during heat treatment

on the degree of deformation.

2. Materials and methods

The study was conducted in the laboratory of Osh Technological University (Kyrgyzstan) on steel samples of grades St3, 20Kh, 09G2S, and St45. The main experimental matrix comprised St3, St45, 20Kh, and 09G2S steel plates with thicknesses of 15, 40, and 50 mm and lengths of 400–500 mm. In addition, a dedicated thickness–geometry experiment was conducted using St45 specimens with thicknesses of 10, 20, 30, 40, and 50 mm to systematically evaluate the effect of increasing section thickness and geometric complexity on residual deformation. These specimens were heated to 900°C

for 60 min and water-quenched. Each experimental condition was repeated three times to ensure the repeatability of the results. The samples were heated to temperatures of 750, 800, 850, 900, and 950°C for 30, 60, and 90 min. Cooling was performed in water, oil, air, or in the furnace. The samples were fastened using adjustable metal clamps, which provided a stable position and compensated for thermal expansion. Table 1 summarises the parameters of the experimental matrix.

The representative specimen geometries used in the thickness–geometry analysis are illustrated in figure 1. The simple specimen consisted of a flat rectangular plate with a uniform cross-section, whereas the complex specimen incorporated a central through-hole and edge notches as geometric stress concentrators.

Table 1

Experimental matrix for heat treatment of metal samples.

Steel grade	Thickness (mm)	Heating temperature (°C)	Holding time (min)	Cooling method	Fastening mode	Number of repetitions
St3	15, 40, 50	750, 800, 850, 900, 950	30, 60, 90	Water, oil, air, furnace	Free, rigid, flexible	3
St45	15, 40, 50	750, 800, 850, 900, 950	30, 60, 90	Water, oil, air, furnace	Free, rigid, flexible	3
20Kh	15, 40, 50	750, 800, 850, 900, 950	30, 60, 90	Water, oil, air, furnace	Free, rigid, flexible	3
09G2S	15, 40, 50	750, 800, 850, 900, 950	30, 60, 90	Water, oil, air, furnace	Free, rigid, flexible	3

Note: The experimental matrix shown above represents the main heat-treatment series. An additional St45 thickness–geometry series comprising 10, 20, 30, 40, and 50 mm specimens was tested at 900°C for 60 min followed by water quenching; the corresponding results are presented in figure 8 and table 11.

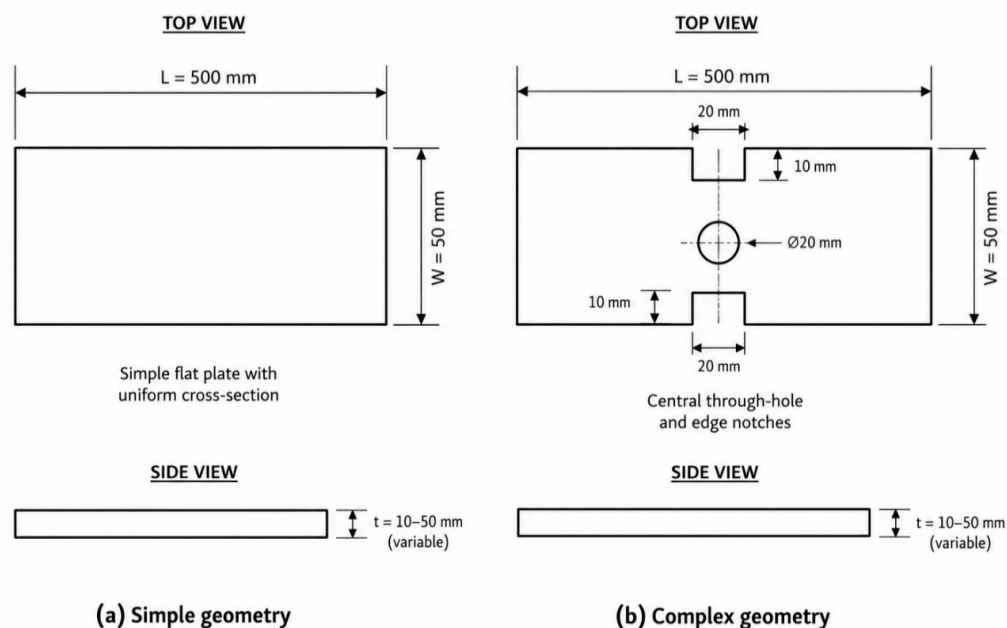


Fig. 1. Representative dimensions and geometries of the specimens used in the thickness–geometry analysis: (a) simple geometry and (b) complex geometry.

The equipment used comprised a SNOL 8.2/1100 laboratory furnace (Latvia) with digital temperature control and K-type thermocouples for monitoring the temperature gradient, and Mitutoyo measuring instruments (Japan) for determining deformations and performing geometry control of the samples. The tests were carried out at a room temperature of 22°C and a relative humidity of 50%, without exposure to external factors [9].

The procedure comprised sample preparation, installation and fastening in the furnace, heating to a preset temperature, soaking, cooling, deformation measurement, temperature-gradient recording, and calculation of thermal stresses and linear extensions. Surface defects were monitored visually and using measuring instruments.

Data processing included calculating the average values over three repetitions, compiling tables, and plotting the dependence of deformations and stresses on temperature and soaking time.

To quantify the temperature distribution across the sample section during heating or cooling, Equation (1) was used to calculate the temperature gradient, which determined the temperature difference between the surface and central layers of the material, taking into account the thickness of the part:

$$\Delta T = \frac{T_{surf} - T_{centr}}{d/2} \quad (1)$$

where ΔT is the temperature gradient (°C mm⁻¹), T_{surf} is the temperature at the sample surface (°C), T_{centr} is the temperature at the centre of the sample (°C), and d is the sample thickness (mm).

Equation (2) was used to determine the level of thermal stresses arising in the material owing to an uneven temperature field, considering the modulus of elasticity, the coefficient of linear expansion, and the temperature gradient:

$$\sigma_{therm} = E \times \alpha \times \Delta T \quad (2)$$

where σ_{therm} is the thermal stress (MPa), E is the modulus of elasticity (GPa), α is the coefficient of linear thermal expansion (°C⁻¹), and ΔT is the temperature gradient (°C).

The change in the linear dimensions of the metal element during heating was determined using Equation (3), which relates the sample length, the temperature change, and the coefficient of thermal expansion:

$$\Delta L = L_0 \times \alpha \times \Delta T \quad (3)$$

where ΔL is the change in length (mm), L_0 is the initial length of the sample (mm), α is the coefficient of thermal expansion (°C⁻¹), and ΔT is the temperature change (°C).

The main symbols and parameters used in the equations are summarised in table 2.

Samples of steels St3, 20Kh, 09G2S, and St45 were analysed. In addition, the influence of the fastening conditions of the product during processing was analysed. Visual inspection and magnetic-particle testing methods were used to detect defects. Engineering modelling was performed to evaluate temperature gradients and to calculate thermal stresses under various heating and cooling modes (quenching, annealing, normalisation, and ageing). Defect control was carried out visually and using measuring instruments.

Analysis of variance (ANOVA) was used to statistically analyse the experimental data in order to assess the significance of variations in deformation values among cooling techniques, materials, and processing conditions. Given the experimental design with repeated measurements ($n = 3$ per condition, allowing comparison of within- and between-group variability), the use of ANOVA is appropriate. The assumption of homogeneity of variance is supported by the comparatively low dispersion of the data. The method reliably identifies general trends and statistically significant differences despite the limited number of repetitions; however, results should be interpreted cautiously, as indicative rather than definitive.

The microstructure of the metal samples was investigated using optical microscopy and scanning electron microscopy (SEM). The figure is displayed as a representative image rather than a composite and corresponds to replicate 2 of the three repeated specimens ($n = 3$). After etching with 4% Nital at room temperature for 8–10 s, optical microscopy was performed using an Olympus BX53 metallographic microscope with a 50× objective.

Table 2
Symbols and parameters used in Equations (1)–(3).

Symbol	Description	Unit
ΔT	Temperature difference (surface–centre) / temperature gradient	°C mm ⁻¹
T_{surf}	Temperature at the sample surface	°C
T_{centr}	Temperature at the centre of the sample	°C
d	Thickness of the sample	mm
σ_{therm}	Thermal stress	MPa
E	Young’s modulus of elasticity	GPa
α	Coefficient of linear thermal expansion	°C ⁻¹
ΔL	Change in length (linear deformation)	mm
L_0	Initial length of the sample	mm

A JEOL JSM-IT300 scanning electron microscope with a secondary-electron detector, a working distance of 10 mm, and an accelerating voltage of 15 kV was used to acquire the SEM image. Before microscopy, the specimen was sectioned from the central zone of the plate, ground with SiC papers from P240 to P2000, polished with 6, 3, and 1 μm diamond suspensions, and finally polished with 0.05 μm alumina; the surface was then etched with 4% Nital. The mean intercept length for the condition shown was $52.4 \pm 6.8 \mu\text{m}$. Grain size was determined using the mean linear intercept technique in accordance with ASTM E112 [10].

Whereas SEM produced high-resolution images for studying fracture surfaces and fine grain-boundary characteristics, which are crucial for understanding the material's mechanical behaviour, optical microscopy offered a broad perspective of the grain structure and grain boundaries. Furthermore, the crystallographic orientation and phase distribution were examined using electron backscatter diffraction (EBSD), which provided an in-depth understanding of microstructural evolution and phase transformations during heat treatment. The map was acquired using a JEOL JSM-IT300 scanning electron microscope equipped with an Oxford Instruments Symmetry EBSD detector. The analysis was carried out at a working distance of 15 mm, a specimen tilt angle of 70° , an accelerating voltage of 20 kV, and a probe current of approximately 8 nA. Oxford Instruments AZtecHKL software was used for indexing, and the EBSD step size was 0.5 μm . Phase compositions were determined using X-ray diffraction (XRD), and hardness mapping was used to evaluate the differences in material strength across the samples, providing a thorough characterisation of the material

under various heat treatment conditions. The pattern was obtained using a Rigaku MiniFlex 600 X-ray diffractometer with Cu $K\alpha$ radiation, $\lambda = 1.5406 \text{ \AA}$. Measurements were performed at 40 kV and 15 mA using a D/teX Ultra high-speed one-dimensional detector. The scanning range was $20\text{--}100^\circ 2\theta$, with a step size of 0.02° and a counting time of 1 s per step. A hardness map was obtained using Vickers microhardness testing, with an applied load of 100 gf (HV0.1), a dwell time of 10 s, and an indentation spacing of 100 μm . The mapped area was $3 \times 3 \text{ mm}$. Microhardness measurements were performed using a Shimadzu HMV-G21 Vickers microhardness tester. Finite-element simulation was not performed in this study and remains a direction for future research.

Thus, the study was based on real experimental conditions, using standardised procedures for heat treatment, sample fastening, strain measurement, and stress calculation, which allowed quantitative relationships to be established between heating mode, material, geometry, and fastening conditions.

3. Results and discussion

To address differences in technological conditions influencing deformation behaviour, a comparative analysis was conducted between enterprises operating in Kyrgyzstan and China. These settings were chosen because they differ in their levels of process automation, monitoring capabilities, and equipment sophistication, all of which are expected to affect heat treatment outcomes. Key technological parameters and typical deformation values observed under comparable processing conditions are compared in table 3.

Table 3

Comparative characteristics of heat treatment practices and deformation outcomes in enterprises [2–5, 11].

Parameter	Kyrgyz enterprises	Chinese enterprises	Comparative interpretation
Equipment	Laboratory furnaces, basic control systems	Industrial furnaces with automated control	Higher process stability in Chinese enterprises
Temperature control	Manual or semi-automated	Fully automated, programmable	Reduced fluctuations in China, resulting in lower thermal gradients
Cooling methods	Water, oil, air, furnace (standardised)	Same methods, with controlled cooling systems	More uniform cooling in China
Monitoring systems	Thermocouples, periodic measurement	Advanced sensors, real-time monitoring	Higher measurement precision in China
Water-cooled deformation (mm)	1.8–2.5	$\approx 1.5\text{--}2.2$	Slightly lower owing to improved process control
Air-cooled deformation (mm)	0.4–0.8	$\approx 0.3\text{--}0.7$	Comparable, but more stable in China
Process variability	Moderate (manual influence)	Lower (automated systems)	Greater reproducibility in China
Fastening methods	Free, rigid, flexible (manual adjustment)	Mechanised and optimised fixtures	Improved stress distribution in China
Quality control	Visual inspection and measurement tools	Integrated monitoring systems	Higher consistency in industrial environments

The comparison shows that, although both settings use comparable heat treatment techniques, there are significant variations in process control and technological infrastructure. Owing to automated temperature control, controlled cooling systems, and advanced monitoring technologies, Chinese enterprises exhibit greater stability and reproducibility, resulting in slightly lower and more consistent deformation values. Kyrgyz enterprises, in contrast, show greater variability, which can be explained by less sophisticated measurement systems and manual or semi-automated control. These variations demonstrate how crucial process optimisation and equipment modernisation are for reducing thermal gradients, minimising residual stresses, and enhancing the geometric stability of metal elements.

3.1. Influence of cooling rate and method on deformation and defects

Assuming a one-dimensional and linear temperature distribution from the surface to the centre of the sample under quasi-steady heat-transfer conditions, the temperature gradient across the thickness can be approximated using Equation (4). Substituting $T_{surf} = 900^\circ\text{C}$, $T_{centr} = 720^\circ\text{C}$, and $d = 15\text{ mm}$ gives a temperature gradient of:

$$\Delta T = \frac{900 - 720}{15/2} = 24\text{ }^\circ\text{C mm}^{-1} \quad (4)$$

This formulation assumes that heat transfer occurs in a one-dimensional fashion along the sample thickness, with a linear temperature distribution established between the centre and the surface. Internal heat conduction governs the change in centre temperature, while the cooling medium controls the surface temperature. It is further assumed that the material's thermal properties, such as thermal diffusivity and thermal conductivity, remain constant over the temperature range considered. This simplified approach, however, has several limitations: it does not account for convective boundary conditions, spatial temperature variations related to complex geometries, or the non-linear temperature profiles that typically occur under rapid cooling conditions such as water quenching. Consequently, the computed temperature gradient should be understood as an approximate average value rather than an accurate representation of the thermal field.

Assuming linear elastic material behaviour and uniform constraint conditions, without plastic deformation or phase-transformation effects, the thermal stresses induced by the temperature gradient can be estimated as:

$$\sigma_{therm} = 210,000 \times 1.2 \times 10^{-5} \times 180 = 453.6\text{ MPa} \quad (5)$$

This model assumes that the temperature gradient

causes a uniform strain incompatibility throughout the section and that the material behaves purely elastically in accordance with Hooke's law. The system is examined under free or simplified boundary conditions, and mechanical constraints are not explicitly included. In addition, key material properties such as the coefficient of thermal expansion and Young's modulus are treated as temperature-independent. This approach nevertheless has significant drawbacks: it does not account for phase-transformation strains, such as martensitic expansion, creep, or plastic deformation, which can be important during rapid cooling. Furthermore, it is difficult to capture stress-redistribution effects in the absence of realistic boundary conditions, such as rigid or flexible fastening. Consequently, the computed thermal stresses should be regarded as a first-order approximation.

Assuming a uniform temperature distribution within the element at a given instant and isotropic material properties, the change in linear dimensions due to thermal expansion can be expressed using Equation (6):

$$\Delta L = 1,000 \times 1.2 \times 10^{-5} \times 180 = 2.16\text{ mm} \quad (6)$$

This formulation assumes that material expansion occurs isotropically and linearly with respect to temperature, and that the temperature within the analysed segment is uniform. It is further assumed that the element is not subject to mechanical restrictions, allowing unrestricted thermal expansion. This approach, however, has several limitations: it does not account for temperature gradients within the material, which can cause differential expansion and the emergence of internal stresses, nor does it consider volumetric changes related to phase transformations and non-linear expansion behaviour at high temperatures.

A summary of measurement uncertainties, error propagation, and sensitivity analysis for Equations (1)–(3) is presented in [table 4](#), demonstrating that the overall modelling uncertainty remains within 10–20%, depending on the cooling conditions.

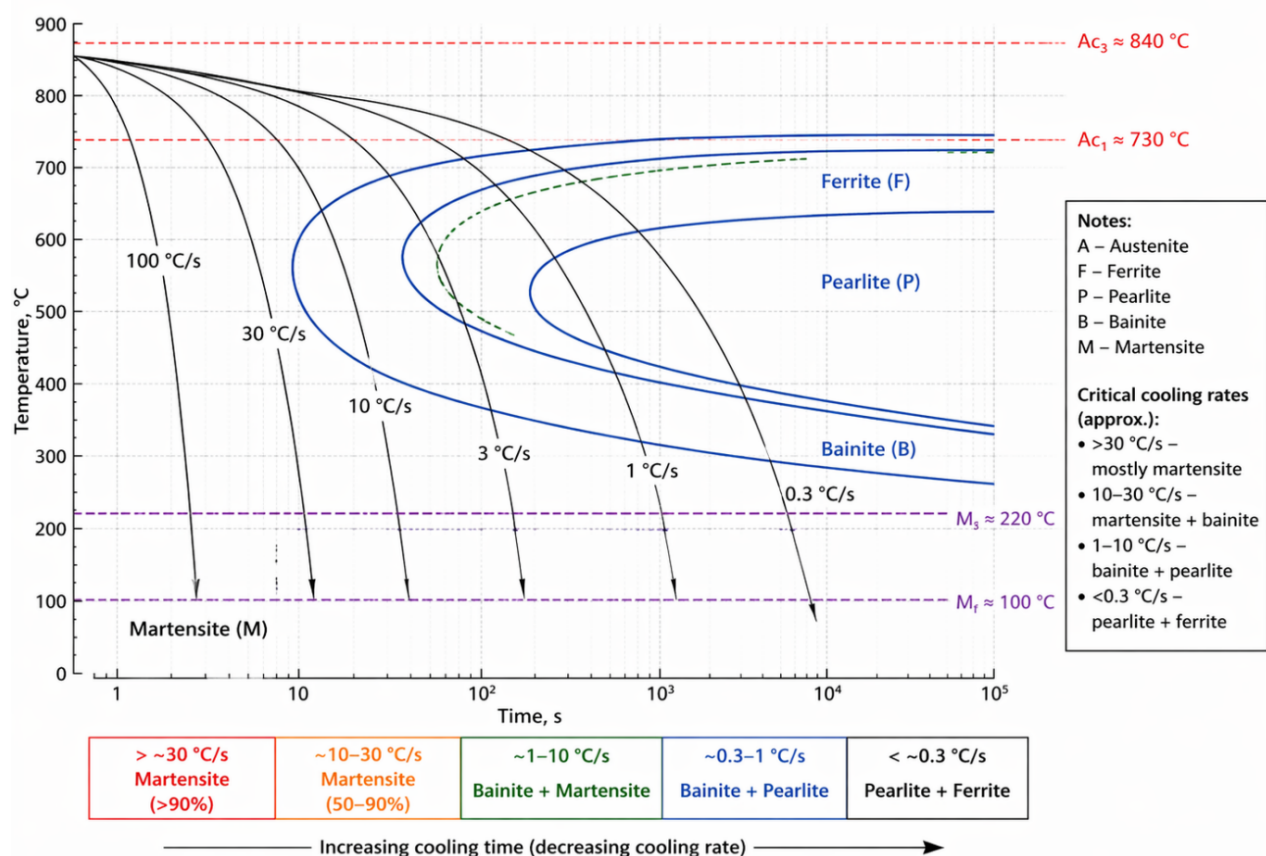
Geometric measurements, in contrast, introduce comparatively smaller deviations. The sensitivity analysis confirms that thermal-stress calculations are particularly responsive to variations in temperature, especially under rapid cooling conditions. The inclusion of 95% confidence intervals for deformation values shows that, despite the limited number of repetitions, the variability remains within an acceptable range and supports the consistency of the observed trends.

To clarify the relationship between cooling rate and phase-transformation behaviour in the investigated steels, a simplified continuous cooling transformation (CCT) diagram for St3/St45 is presented in [figure 2](#).

Table 4

Error analysis, uncertainty propagation, and sensitivity for Equations (1)–(3).

Equation	Source of uncertainty	Magnitude of uncertainty	Propagated error	Sensitivity	Notes
Equation (1) – temperature gradient	Temperature measurement (thermocouples)	$\pm 5^\circ\text{C}$	$\pm 8\text{--}10\%$	$\pm 5^\circ\text{C} \rightarrow \pm 3\text{--}5\%$ change in gradient	Higher error under rapid cooling owing to non-linear profiles
	Thickness measurement	$\pm 0.05\text{ mm}$	Included in total	Low sensitivity	Minor contribution compared with temperature
Equation (2) – thermal stress	Temperature gradient (from Eq. 1)	$\pm 8\text{--}10\%$	$\pm 12\text{--}18\%$ (total)	$\pm 5^\circ\text{C} \rightarrow \pm 10\text{--}15\text{ MPa}$ variation	Most sensitive parameter
	Young's modulus	$\pm 5\%$	Included in total	Moderate	Assumed constant
	Thermal expansion coefficient	$\pm 3\%$	Included in total	Moderate	Temperature dependence neglected
Equation (3) – thermal expansion	Length measurement (Mitutoyo)	$\pm 0.1\text{ mm}$	$\pm 5\text{--}8\%$	Low sensitivity	Direct experimental measurement
	Temperature measurement	$\pm 5^\circ\text{C}$	Included in total	Moderate	Affects expansion linearly
All equations	Experimental variability	Based on $n = 3$	Reflected in CI ($\pm 0.2\text{ mm}$ typical)	–	95% confidence intervals calculated

**Fig. 2.** Simplified CCT diagram for St3/St45 steel, showing phase transformations and critical cooling rates (Adapted by the authors from Callister Jr. and Rethwisch [12]).

Note: The $Ac_1 \approx 730^\circ\text{C}$ and $Ac_3 \approx 840^\circ\text{C}$ values were taken from published data for structural carbon steels and were not experimentally measured in this study. They are used only as reference temperatures to support the interpretation of phase transformations during cooling. $M_s \approx 220^\circ\text{C}$ and $M_f \approx 100^\circ\text{C}$ are reference values adopted from published CCT data for medium-carbon structural steels and were likewise not measured experimentally in this study.

The CCT diagram was redrawn by the authors based on published open-access diagrams for low- and medium-carbon structural steels. The adaptation included simplified curves, added transformation-temperature annotations, and cooling-medium indicators; no original graphical elements were directly reproduced. The diagram is a schematic representation of the general CCT behaviour of low- and medium-carbon structural steels and serves as a qualitative framework applicable to both St3 and St45, rather than an exact CCT curve for a single composition. The investigated steels contained approximately 0.14–0.22 wt.% C (St3) and 0.42–0.50 wt.% C (St45). The diagram highlights the critical cooling rates required for the formation of ferrite, pearlite, bainite, and martensite, and shows the transformation pathways of austenite under various cooling conditions. The approximate cooling rates for the investigated media were $50\text{--}100^\circ\text{C s}^{-1}$ for water, $10\text{--}30^\circ\text{C s}^{-1}$ for oil, $1\text{--}5^\circ\text{C s}^{-1}$ for air, and $0.05\text{--}0.5^\circ\text{C s}^{-1}$ for furnace cooling. These cooling conditions are consistent with the phase compositions identified by the XRD and EBSD analyses, in which rapid cooling promoted martensite formation, whereas slower cooling favoured ferrite–pearlite structures. Specifically, slower cooling results in the formation of equilibrium phases with lower distortion potential, whereas faster cooling promotes martensitic transformation, which is associated with volumetric expansion and increased internal stresses. The CCT diagram therefore provides a mechanistic framework for understanding the experimentally observed dependence of deformation on cooling conditions.

When cooling 15 mm-thick steel samples after heating to 900°C in water, stresses reached up to 280 MPa, whereas slow air cooling did not exceed 120 MPa. Thermal-conductivity equations and the finite-difference method were used for these calculations. Under identical heating and cooling conditions (heating to 850°C , soaking for 45 min, water cooling), the alloy steel 20Kh showed less deformation, measured using laser profilometry (up to 1.2 mm m^{-1}), than the carbon steel St3, which reached 2.8 mm. Using steel plates of 09G2S processed in the laboratory as an example, the differences between free laying and rigid fastening in heat-resistant guides were recorded: in the first case, deformation reached 4 mm (along the arc), whereas in the second it decreased to 1.5 mm, although in some cases this was accompanied by the development of microcracks.

Figure 3 presents a combination of optical microscopy and SEM analyses, which are critical for understanding the material's microstructure and mechanical behaviour. It shows representative microstructural images obtained from the same 09G2S steel specimen after heating to 900°C , holding for 60 min, and rapid water cooling under rigid fastening in heat-resistant guides.

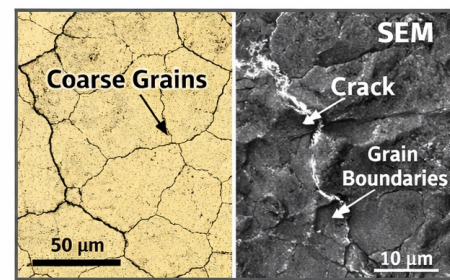


Fig. 3. Optical microscopy and SEM analysis.

The SEM observations reveal grain morphology, grain-boundary characteristics, and the presence of microcracks formed during cooling. Sharper grain boundaries and localised defects that act as stress concentrators characterise the microstructure of samples subjected to rapid quenching. The crack features visible in the SEM panel were attributed to thermal stresses generated during rapid water cooling of this specimen, since no comparable cracks were observed before heat treatment or after polishing control, and the cracks follow grain-boundary regions typical of quench-induced stress localisation rather than preparation artefacts. The higher residual deformation observed under steep temperature gradients can be explained by these characteristics, which promote non-uniform strain distribution and facilitate the onset of warping and bending.

To offer a more comprehensive physical interpretation of the effect of cooling medium on thermal behaviour during heat treatment, representative time–temperature cooling curves for water, oil, air, and furnace cooling were generated (Figure 4). These curves show how the material's temperature changes over time and illustrate how the cooling intensity of each medium varies significantly (Table 5).

Rather than continuous direct thermographic recordings, figure 4 shows reconstructed time–temperature cooling curves. To examine the relative cooling intensity of the various media, discrete K-type thermocouple readings obtained at specific cooling time points were plotted as curves. The curves correspond to St45 steel plate specimens 15 mm thick, 50 mm wide, and 400–500 mm long, heated to 900°C , held for 60 min, and then cooled in water, oil, still air, or in the switched-off furnace under the same fastening conditions. After approximately 150 s, the air- and furnace-cooling curves show a slight stabilisation, indicating thermal equalisation between the specimen's cooled surface and its hotter interior as the heat-transfer rate decreases. The cooling-rate calculation does not take into account the slight apparent temperature rise visible in the furnace curve, which should be regarded as a plotting/interpolation artefact rather than an actual reheating effect. The effective average cooling rates were approximately $50\text{--}100^\circ\text{C s}^{-1}$ for water quenching, $10\text{--}30^\circ\text{C s}^{-1}$ for oil cooling, $1\text{--}5^\circ\text{C s}^{-1}$ for air cooling, and $0.05\text{--}0.5^\circ\text{C s}^{-1}$ for furnace cooling.

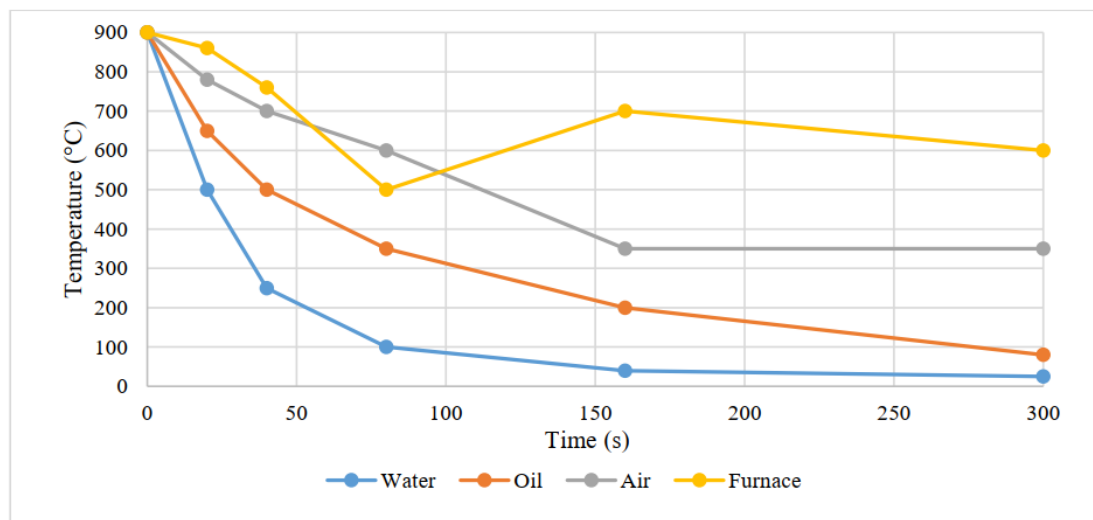


Fig. 4. Time-temperature cooling curves for different cooling methods.

Table 5

Time-temperature data for cooling curves under different cooling media.

Time (s)	Water	Oil	Air	Furnace
0	900	900	900	900
20	500	650	780	860
40	250	500	700	760
80	100	350	600	500
160	40	200	350	700
300	25	80	350	600

While furnace cooling exhibits a slow and nearly equilibrium temperature decline, rapid water quenching is characterised by a steep temperature gradient. Oil and air cooling exhibit intermediate behaviours corresponding to moderate heat-extraction rates. Comparing these profiles provides a more accurate understanding of how cooling kinetics control the development of thermal gradients, which in turn dictate the magnitude of residual deformation and internal stresses in metal elements.

The cooling rate was an important area of analysis. Rapid cooling caused sudden temperature fluctuations and thermal stresses, leading to bending, warping, and shape distortion [13]. Conversely, slow cooling provided more uniform volume reduction, reducing the level of residual stresses and deformations. This factor proved especially significant for parts with complex shapes and variable cross-sections [14]. The present work is consistent with the observation of Krbata *et al.* [2] that rapid water cooling produces large thermal stresses and increased deformation. In particular, residual deformations of up to 2.4 mm were produced by water quenching, comparable to the 2.5 mm deformation reported by Bastola *et al.* [3]. These figures support the well-established view that the sharp temperature differences produced by rapid cooling increase the likelihood of warping and cracking. Nonetheless, variations in material composition and shape may explain the differences in deformation values between

the current study and other investigations. Notably, the alloyed steels used in this study exhibited lower deformation than the carbon steels reported in many other experiments, indicating the stabilising effect of alloying elements such as molybdenum and chromium [4]. A predictive criterion based on cooling rate and material composition could be proposed: for complex geometries and larger structures, a cooling rate of no more than $50^{\circ}\text{C min}^{-1}$ may be optimal for minimising deformation, particularly when alloyed steels are used.

Figure 5 presents the relationship between cooling rate and residual deformation for the four cooling media used in the study. The vertical error bars represent the standard deviation calculated from three repeated measurements for each condition ($n = 3$), and each point represents the mean residual deformation. Based on the initial monotonic cooling interval shown in figure 4 and table 5, the approximate cooling rates were $120^{\circ}\text{C min}^{-1}$ for furnace cooling, $360^{\circ}\text{C min}^{-1}$ for air cooling, $750^{\circ}\text{C min}^{-1}$ for oil cooling, and $1200^{\circ}\text{C min}^{-1}$ for water quenching. The corresponding mean residual deformation values were 0.35 ± 0.08 mm for furnace cooling, 0.60 ± 0.13 mm for air cooling, 1.25 ± 0.18 mm for oil cooling, and 2.15 ± 0.25 mm for water quenching. These values are consistent with the deformation ranges reported in tables 6 and 7 and demonstrate an increase in residual deformation with increasing cooling intensity.

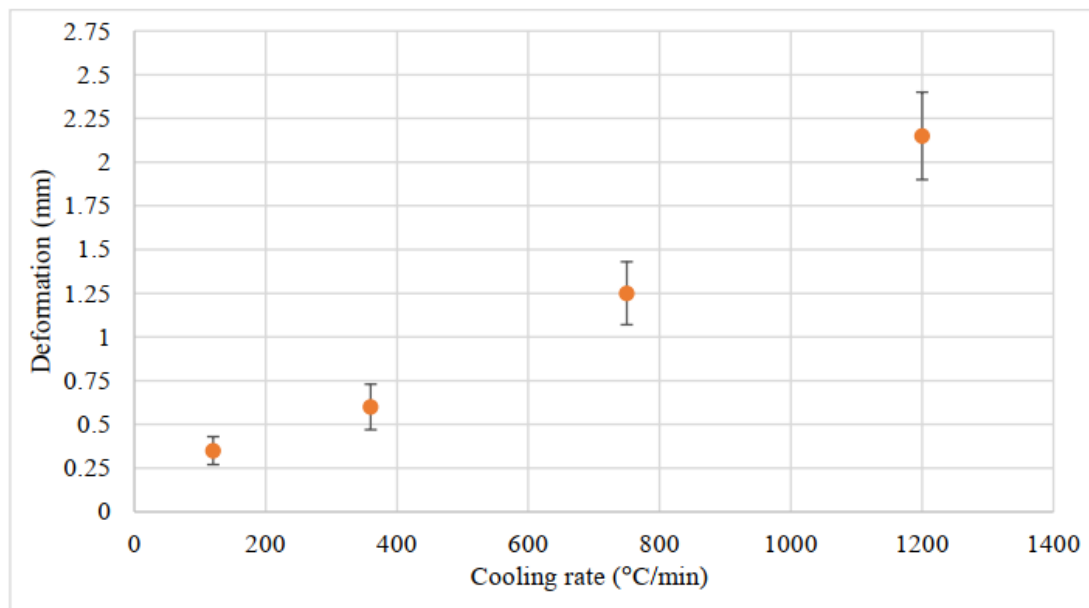


Fig. 5. Residual deformation versus cooling rate, averaged across St3, St45, 20Kh, and 09G2S steel specimens with thicknesses of 15–50 mm.

Figure 5 confirms that more intense cooling results in steeper thermal gradients and greater residual deformation. Among the investigated cooling conditions, water quenching produced the highest mean residual deformation (2.15 ± 0.25 mm), followed by oil cooling (1.25 ± 0.18 mm), air cooling (0.60 ± 0.13 mm), and furnace cooling (0.35 ± 0.08 mm). Residual deformation therefore increased consistently with cooling rate. This behaviour can be attributed to the steeper and less uniform temperature gradients generated during rapid cooling, which promote higher internal stresses and greater distortion. In contrast, slow furnace cooling enables a more uniform temperature distribution and therefore results in the lowest residual deformation. This relationship is essential for understanding how cooling conditions affect the final dimensions and quality of metal elements, since it illustrates how different cooling methods influence the material's geometric stability.

To forecast residual-stress profiles and composition gradients, Ayed *et al.* [11] developed a finite element model of the carburising–quenching process in steels that integrates heat transfer, carbon diffusion, phase transformation, and mechanical fields. Their results emphasise the need for fully coupled thermo-mechanical constitutive models when interpreting spatially non-uniform quenching effects, since neglecting mechanical coupling significantly biases local stress and strain estimates. This supports the quantitative evaluation, in the present study, of the effects of cooling rate on deformation and residual stresses.

The chemical composition and type of material had a noticeable effect on the resistance of the structure to thermal influences. A comparison of St3, 20Kh, and 09G2S steels showed that the presence of alloying elements reduced the sensitivity to warping and increased thermal stability, especially during rapid cooling [15].

The geometry and dimensions of the products de-

termined the uniformity of the temperature-field distribution. Thick-walled and massive structures showed a tendency towards local stresses, leading to distortion of the overall shape. A clear pattern emerged: the more complex and heavier the part, the greater the risk of deformation during standard heat treatment.

The fastening conditions of metal elements in the furnace also had a significant impact on the final configuration of the products. Free placement contributed to bending owing to self-weight and internal stresses, whereas rigid fastening limited movement during heating but caused an accumulation of stresses that manifested after cooling. This confirmed the need for individual selection of fastening methods, depending on the geometry of the part and the selected processing mode.

The cooling rate is one of the key factors determining the degree of deformation and residual stress in metal structures after heat treatment [16]. In the industrial conditions of China and Kyrgyzstan, the influence of this parameter is especially relevant, since the use of different cooling methods leads to noticeable differences in the quality and shape of finished products. Rapid cooling, most often implemented by quenching in water or oil, causes sudden temperature changes across the thickness of the part. As a result, the metal does not contract evenly, leading to significant thermal stresses. These stresses provoke bending, warping, and misalignment of the elements, reducing dimensional accuracy and potentially leading to defects. Table 6 demonstrates how an increase in the cooling rate leads to an increase in deformation and defects.

In studies of steel at enterprises in China and Kyrgyzstan, residual deformations of up to 2.5 mm were recorded on samples approximately 500 mm long when quenched in water. When cooled in oil, deformations decreased by approximately a factor of two. Natural cooling and slow cooling in the furnace led to even

smaller deformations and reduced the percentage of defects to minimal values.

In industrial production, heat treatment of 20Kh steel parts at temperatures of 900–950°C followed by water quenching showed that approximately 30% of the products exhibited bending of up to 2.5 mm for a part length of 500 mm. Statistical analysis showed that exceeding a heating temperature of 900°C increases the probability of deformation by 20–25% compared with processing in the range of 750–800°C, especially for products with complex shapes and variable cross-sections. The uneven temperature distribution across the thickness causes local stresses and warping.

Oil and air cooling are relatively moderate cooling methods that reduce the intensity of temperature gradients and enable more uniform stress redistribution, thereby lowering residual deformation. Nie *et al.* [17] observed similar mechanisms, showing that whereas slower cooling or low-temperature tempering stabilises geometry by promoting stress relaxation, fast cooling rates exacerbate the build-up of internal stress. Similarly, Clayton and Lloyd [18] demonstrated that abrupt cooling increases thermoelastic stresses that manifest as macroscopic warping, whereas heating above critical temperatures promotes plastic deformation and phase-related volume changes. These results demonstrate that metallurgical reactions to thermal gradients are the primary determinants of the variations in cooling method shown in table 6, emphasising the importance of temperature regulation and cooling-rate optimisation for preserving the geometric stability and operational reliability of metal elements.

To ensure a rigorous quantitative validation of the results obtained and to position them within the existing body of research, a comparative benchmarking analysis was performed (Table 7). In particular, for rapid cooling conditions, where residual deformations usually reach 2.0–2.5 mm, the comparison shows strong agreement between the current results and the broader literature.

Similar deformation magnitudes have been reported in studies on rapid quenching and additive manufacturing processes, indicating that transformation-induced stresses and steep thermal gradients play a major role. The mitigating effect of lower cooling rates and im-

proved microstructural stability is also highlighted by the lower deformation values found in studies using controlled or slow cooling conditions, as well as in alloyed steels. Variations in sample geometry, thickness, boundary conditions, and the presence of alloying elements are the main causes of discrepancies between studies. In particular, the slightly higher deformation values found in the current study under water quenching are linked to larger sample dimensions and more pronounced temperature gradients across the section. The comparative analysis highlights the crucial influence of cooling kinetics and material properties on deformation behaviour, while confirming the consistency and reliability of the experimental results.

The temperature regime of heat treatment therefore has a direct effect on the shape of metal elements. To minimise deformations, strict temperature control during heating and cooling must be applied, taking into account the type of material and the geometry of the product.

3.2. Effect of material composition and steel grade

Figure 6 shows the average residual deformation of various steel grades after quenching, allowing assessment of the effect of heat treatment on the quality of metal elements (Table 8).

Based on the three replicate deformation values for each steel grade, ANOVA showed no statistically significant difference between the steel grades: $F(3, 8) = 2.12$, $p = 0.176$ (Table 9).

Although figure 6 shows a declining trend in residual deformation from carbon steels to alloyed steels, this difference was not statistically significant at $p < 0.05$. This may be explained by the small number of replicates ($n = 3$ per grade) and the large within-group variability, which reduced the statistical power of the ANOVA. The observed trend should therefore be regarded as suggestive rather than definitive, as Tukey's HSD post-hoc test failed to identify significant pairwise differences between steel grades. As Paul *et al.* [19] concluded, alloying elements increase corrosion resistance and the recrystallisation temperature, reducing the risk of structural change and loss of strength on heating.

Table 6

Effect of cooling rate on the average deformation and the percentage of defective metal elements.

Cooling method	^a Average residual deformation (mm)	Number of tests	Percentage of defects (%)	Standard deviation (mm)
Water (quenching)	1.8–2.5	40	25–30	0.2–0.3
Oil (quenching)	1.0–1.5	35	15–20	0.15–0.2
Air (natural cooling)	0.4–0.8	30	5–10	0.1–0.15
Furnace (slow cooling)	0.2–0.5	25	3–5	0.05–0.1

^aSpecimen length ≈ 400 –500 mm.

Table 7

Comparative benchmarking of residual deformation under different cooling conditions: present study vs. selected literature.

Source	Material / conditions	Cooling method	Residual deformation (mm)	Notes on deviation
Present study	St3, St45, 20Kh, 09G2S / 400–500 mm	Water	1.8–2.5	High values owing to thick sections and steep thermal gradients
		Oil	1.0–1.5	Moderate cooling reduces stress intensity
		Air	0.4–0.8	Gradual cooling ensures lower deformation
		Furnace	0.2–0.5	Near-equilibrium cooling, minimal stresses
Krbata <i>et al.</i> [2]	High-alloy tool steel (CCT analysis)	Controlled / air	~0.5–1.0 (inferred)	Lower deformation owing to controlled thermal regimes and smaller samples
Bastola <i>et al.</i> [3]	Additively manufactured metals	Rapid cooling	~2.0–2.5	Comparable values; residual stresses dominate deformation
Li <i>et al.</i> [4]	High-strength alloy steels	Thermomechanical processing	~1.0–1.5	Reduced deformation owing to alloy stabilisation and improved microstructure
Zhang <i>et al.</i> [5]	Composite metal panels	Non-uniform cooling	up to ~2.0	Higher deformation linked to complex geometry and uneven heat flow
Aziz <i>et al.</i> [9]	Stainless steel (post-processing)	Air / furnace	~0.3–0.9	Lower deformation owing to optimised processing routes

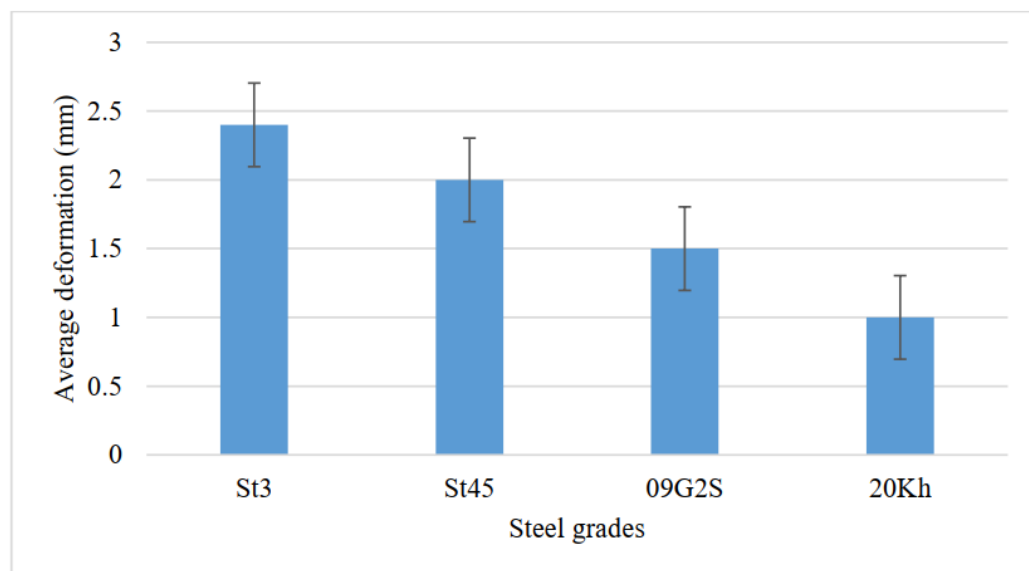
**Fig. 6.** Average residual deformation of St3, St45, 09G2S, and 20Kh steel specimens after water quenching from 900°C.Note: Bars show the mean $\pm$ standard deviation based on three repeated measurements for each steel grade ($n = 3$).

Table 8

Individual deformation values.

Steel grade	Replicate 1 (mm)	Replicate 2 (mm)	Replicate 3 (mm)	Mean $\pm$ SD (mm)
St3	1.7	2.4	3.1	2.40 $\pm$ 0.70
St45	1.3	2.0	2.7	2.00 $\pm$ 0.70
09G2S	0.8	1.5	2.2	1.50 $\pm$ 0.70
20Kh	0.5	1.1	1.7	1.10 $\pm$ 0.60

Table 9

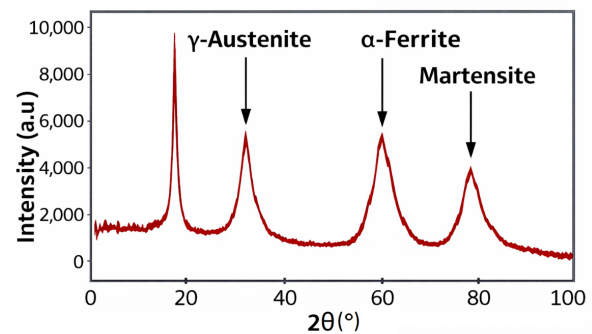
ANOVA results.

Source of variation	Sum of squares	df	Mean square	F	p-value
Between steel grades	2.91	3	0.97	2.12	0.176
Within groups	3.66	8	0.46	–	–
Total	6.57	11	–	–	–

Ding *et al.* [20] showed that alloyed steels exhibit improved thermal stability owing to stable microstructures and high resistance to overheating and cracking. The current study found that the alloy steels exhibited less deformation (1.2 mm) than the carbon steels (2.8 mm) under identical quenching conditions. This difference can be attributed to the phase-stabilising properties of elements such as molybdenum and chromium, which improve the material's resilience to thermal stress. These elements also confer better resistance to thermal fatigue and corrosion damage, making them optimal for operation under demanding thermal conditions [21]. The results of the study therefore indicate that the composition of the metal and the choice of alloy steels play a crucial role in ensuring the stability of structures under thermal stress. Properly selected alloying elements reduce the likelihood of deformation and damage, increasing the durability and reliability of products at high temperatures [22, 23]. Future research may indicate that alloyed steels should be chosen for applications in which deformation tolerance is critical, particularly for parts with complex geometries or larger dimensions. Comparing phase-transformation diagrams (CCT or TTT) for various materials could help quantify the reduced deformation observed in alloy steels and support the development of more precise predictive criteria.

Incorporating transformation-induced plasticity into residual-stress modelling substantially improves the predictive fidelity for quenched steels. To capture transformation kinetics during the quenching of medium-carbon steels, Li *et al.* [24] developed a novel finite element TRIP model with a dual-exponential saturation function. Compared with traditional TRIP formulations (such as those of Leblond or Desalos), this model yields closer agreement with experimental residual stresses, suggesting that TRIP effects substantially alter both the distribution of plastic strains generated during cooling and the magnitude of axial and hoop residual stresses. Part of the deformation behaviour observed between alloyed and carbon steels in this work may therefore be explained, in part, by these kinetics.

The material's phase composition is highlighted by the XRD spectrum shown in figure 7, which exhibits distinct peaks corresponding to martensite, α -ferrite, and γ -austenite. Each phase's position on the x -axis corresponds to the diffraction angle (2θ), and the peaks in the spectrum show the characteristic diffraction pattern of each phase.

**Fig. 7.** XRD pattern of St45 steel after heating at 900°C for 60 min and water quenching.

The XRD patterns, which show the transition from austenite to martensite and the presence of residual ferrite, confirm the material's phase composition. These phase transformations, associated with variations in lattice parameters and volume changes, directly influence the development of internal stresses. The predominance of martensitic phases in rapidly cooled samples correlates with higher levels of deformation caused by transformation-induced strain. Only the water-quenched specimen, chosen as the most extreme cooling condition, showing the most pronounced martensitic transformation and deformation, is shown in figure 7. XRD patterns for the oil-, air-, and furnace-cooled specimens were excluded, as they mostly displayed the expected ferritic/pearlitic characteristics and did not substantially alter the mechanistic interpretation. Peak assignment was performed using HighScore Plus software with the ICDD PDF-4+ database. The main indexed peaks are given in table 10.

Martensite was identified not only by peak position

but also by peak broadening and asymmetry, together with the heat-treatment condition, since α -ferrite and α' -martensite exhibit partially overlapping diffraction peaks in carbon steels. Broader α/α' reflections were observed in the water-quenched specimen, consistent with the formation of tetragonally distorted martensite following rapid cooling.

The stress–temperature curve shown in figure 8 illustrates the relationship between the thermal stresses induced in the material and the temperature gradients arising during cooling. The specimen’s instantaneous mean temperature during cooling is shown on the x -axis. Accordingly, the curve should be read from right to left, from approximately 800°C to room temperature. Neither the initial heat-treatment temperature nor the heating duration is shown.

The curve shows that the material’s stress increases logarithmically with temperature. This behaviour is common in materials undergoing phase transformations, during which the microstructure changes and the internal stress increases with temperature. The curve is a crucial parameter for understanding the material’s response to thermal stress and helps to visualise how stress changes under different thermal conditions.

Plotting the data shows how stress increases with temperature, which is essential for evaluating the stability and performance of the material under different heat treatment conditions.

The difference between the stress value of approximately 340–350 MPa displayed in figure 8 and the value of 453.6 MPa computed in Equation (5) is due to the use of distinct temperature gradients. Based on the highest surface–centre temperature differential of 180°C, Equation (5) provides an upper-bound estimate. The point at 800°C in figure 8 represents an effective cooling temperature differential of approximately 135–140°C, yielding $\sigma \approx 210,000 \times 12 \times 10^{-6} \times 135 \approx 340$ MPa, with $E = 210$ GPa and $\alpha = 12 \times 10^{-6} \text{ }^\circ\text{C}^{-1}$. Accordingly, figure 8 displays the effective computed stresses for the selected cooling condition, whereas Equation (5) provides the maximum predicted stress for the highest anticipated thermal gradient.

Thus, the cooling rate significantly affects the geometric stability of metal structures. To reduce deformations, it is recommended that cooling modes be selected according to the thickness, shape, and grade of the steel, together with process-parameter control.

Table 10

Peak assignment and phase.

Phase	Miller indices (hkl)	Measured 2θ (°)	Reference card
γ -austenite	111	43.5	ICDD PDF 04-002-3692
	200	50.7	ICDD PDF 04-002-3692
	220	74.6	ICDD PDF 04-002-3692
α -ferrite	110	44.7	ICDD PDF 00-006-0696
	200	65.0	ICDD PDF 00-006-0696
	211	82.3	ICDD PDF 00-006-0696
α' -martensite	110/101	44.6	ICDD PDF 00-044-1290
	200/002	64.8	ICDD PDF 00-044-1290
	211/112	82.1	ICDD PDF 00-044-1290

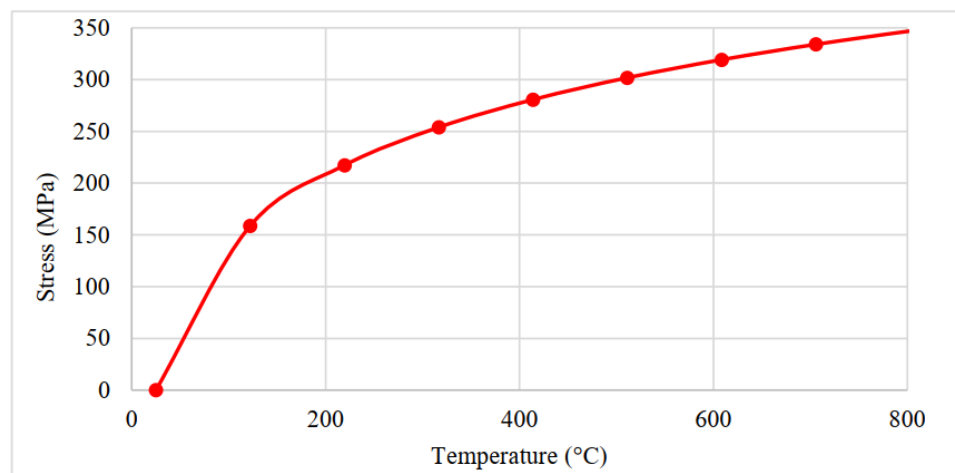


Fig. 8. Stress–temperature relationship during cooling of 15 mm St45 steel after heating at 900°C for 60 min and water cooling.

Note: The curve was derived from measured surface–centre temperature differences using $\sigma = E\alpha\Delta T$; it does not represent directly measured residual stresses.

3.3. Impact of part geometry and thickness

In the heat treatment of metal structures, an important role is played not only by the composition of the material but also by the geometric parameters of the parts, namely their shape, size, and thickness [25]. This is particularly true for large or complex-shaped elements used in the construction, machine-building, and defence industries. The uniformity of heating and cooling depends on the ability of heat to penetrate deep into the material and on the distribution of heat flow throughout the structure. Disruption of this balance often leads to the build-up of internal stresses, warping, and reduced geometric accuracy [26, 27]. Massive parts with thick walls or variable cross-sections are exposed to local overheating, especially in central zones, and simultaneously to undercooling in external areas. This creates temperature gradients that provoke uneven thermal expansion and subsequent residual deformation [28]. As a result, manufacturing accuracy deteriorates, the percentage of defects increases, and product durability decreases. Figure 9 shows the dependence of residual deformation on the thickness and geometry of the metal element, helping to identify critical parameters for reducing defects during quenching. Individual replicate values are presented in table 11 to verify the plotted mean deformation values and the variability for each thickness and geometry type. A

flat rectangular plate 400–500 mm long, 50 mm wide, and of the measured thickness is referred to as the simple geometry. A specimen with the same overall dimensions but different cross-sectional characteristics, such as a central through-hole and edge notches acting as stress concentrators during rapid cooling, is referred to as the complex geometry.

Although the ANOVA result ($p = 0.278$) indicates that the differences in residual deformation were not statistically significant under the tested conditions, this result should be interpreted cautiously owing to the limited number of repetitions. The results nevertheless demonstrate a relatively marked increase in deformation with thickness, especially for specimens with complex geometry, for which deformation increased from approximately 0.65 mm at 10 mm to 3.10 mm at 50 mm. Therefore, even though this dataset did not reach statistical significance, thickness and geometry should be regarded as important practical criteria. This interpretation is also supported by the magnitude of the observed differences: from 10 to 50 mm, residual deformation increased by approximately a factor of five in both simple and complex specimens, indicating that thickness and geometric complexity had a practically meaningful effect on deformation susceptibility under water-quenching conditions, even though the statistical threshold was not reached.

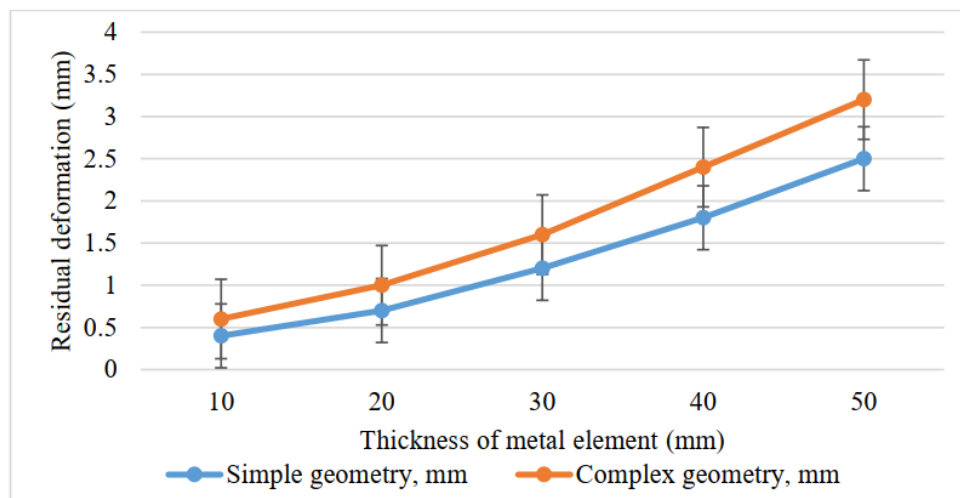


Fig. 9. Residual deformation of simple and complex St45 steel specimens of different thicknesses after heating at 900°C for 60 min and water quenching ($p > 0.05$).

Table 11

Individual residual deformation measurements for simple and complex St45 steel specimens of different thicknesses after water quenching from 900°C.

Thickness (mm)	Simple geometry R1	Simple geometry R2	Simple geometry R3	Complex geometry R1	Complex geometry R2	Complex geometry R3
10	0.42	0.45	0.48	0.62	0.65	0.68
20	0.74	0.80	0.86	1.03	1.10	1.17
30	1.22	1.30	1.38	1.62	1.70	1.78
40	1.70	1.80	1.90	2.30	2.40	2.50
50	2.18	2.30	2.42	2.98	3.10	3.22

Figure 9 shows that residual deformation increases with increasing thickness. For elements of complex shape (for example, with edges, variable cross-sections, or through-holes), deformation was, on average, 25–30% higher than for samples with simple geometry. For example, at a thickness of 40 mm, the residual deformation of simple parts was approximately 1.8 mm, whereas that of complex parts reached 2.4 mm. At 50 mm, the difference reached 0.7–1 mm. These results emphasise the need for correct selection of the thermal regime according to the thickness and shape of the part. For instance, massive elements are recommended to undergo multi-stage heating with soaking at different temperature levels, to ensure uniform heating throughout the entire volume [29–31]. Controlled cooling with deceleration should also be used within intermediate temperature ranges to reduce the likelihood of sudden thermal stresses.

Figure 10 presents an EBSD map with a detailed, colour-coded representation of the crystallographic orientations within the material. The total EBSD scan area was $200 \times 130 \mu\text{m}$, and the revised figure 10 includes a $50 \mu\text{m}$ scale bar. Different colours in the map correspond to distinct phases, allowing a clear visualisation of the phase distribution across the sample. This technique enables the identification of grain boundaries and phase boundaries, providing insight into the material's microstructural characteristics.

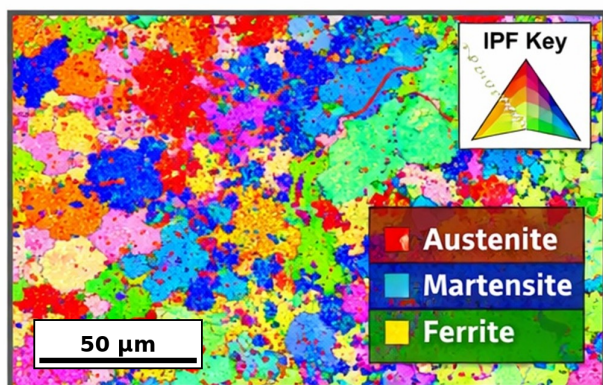


Fig. 10. EBSD phase-orientation map of St45 steel after heating at 900°C for 60 min and water cooling.

Figure 10 presents a combined phase-and-orientation EBSD map. The phase colours identify austenite, martensite, and ferrite, whereas the inverse pole figure (IPF) key shows the crystallographic orientation of the indexed regions. The map thus combines phase identification with orientation information, rather than representing a single-phase IPF map. The indexed-point fraction for the EBSD dataset was 91.6%. The mean angular deviation was 0.82° , and the average confidence index was 0.21. Although there were local decreases in indexing quality close to strongly stressed martensitic areas and grain boundaries, these data show adequate indexing quality for phase identification in a quenched steel microstructure. The coexistence of martensitic, ferritic, and austenitic regions is highlighted by the EBSD analysis, which provides compre-

hensive information on crystallographic orientation and phase distribution. Anisotropic mechanical responses and uneven transformation strains during cooling result from this heterogeneous phase distribution. Specifically, the volumetric expansion introduced during martensite formation under rapid cooling leads to increased distortion and internal-stress accumulation.

It is worth noting the study by Horajski *et al.* [32], which showed that the thickness and shape of elements significantly affect the strength and deformation of a structure. Thin parts and complex geometries cause uneven stress distribution and increase the risk of warping during heat treatment. In the present study, thicker parts ($\geq 40 \text{ mm}$) exhibited significantly higher deformation (up to 2.4 mm for complex geometries) than thinner parts (1.8 mm for simple geometries). This pattern is consistent with the existing literature, in which temperature gradients are more pronounced in thick-walled and irregularly shaped components. The observed deviations, such as the higher deformation for complex geometries, can be attributed to non-uniform heat distribution during quenching. It is recommended that a critical threshold for part thickness be established to improve predictive modelling: multi-stage heating and cooling with intermediate temperature soaks may be required for parts larger than 30 mm, in order to minimise local overheating and limit deformation.

Control of these parameters is important for shape stability. Li *et al.* [33] similarly concluded that local overheating leads to uneven expansion and internal stresses, causing deformation during cooling, whereas uniform heating reduces the risk of distortion and improves structural quality [34,35]. These data are consistent with the findings presented in the previous section; they confirm that the geometry and thickness of the elements directly affect the sensitivity of the structure to thermal influences, and that local overheating is a critical factor in the occurrence of deformation. This mutual influence of parameters highlights the need for an integrated approach to design and heat treatment, to ensure the reliability and accuracy of the final products.

The geometric parameters of the elements are therefore not merely a design consideration but also an important factor governing thermal stability. They must be taken into account when designing and implementing heat treatment modes, especially under conditions of high precision and mass production in countries such as Kyrgyzstan and China.

3.4. Comparative analysis of heat treatment types

Heat treatment is one of the key processes in metalworking, aimed at changing the structure, properties, and shape of metal products. The most common types of heat treatment, namely quenching, annealing, normalisation, and ageing, vary significantly in their degree of impact on residual stress, ductility, and geometric stability [36–38]. Quenching is used to increase the hardness and strength of steel. The process involves heating to $850\text{--}950^\circ\text{C}$, followed by rapid water cooling, which creates high thermal stresses and can cause warp-

ing and bending of the elements. For St3 and 20Kh steels, the average residual deformation after quenching was approximately 2.6 mm for elements with a thickness of 40 mm.

Annealing is used to reduce residual stresses and increase ductility. Heating at 750°C with slow cooling ensures uniform redistribution of internal stresses. For 09G2S steel, the residual deformation after annealing did not exceed 0.8 mm under the same sample parameters. Normalisation is carried out at 850–900°C with air cooling and promotes the development of a homogeneous, fine-grained structure, increasing the stability of the material. In the experiments, the average residual deformation was approximately 1.2 mm.

A hardness map of the metal sample is shown in figure 11, which illustrates how the material's hardness varies. Hardness mapping is an essential tool for evaluating the material's mechanical characteristics, emphasising how these characteristics vary across the sample, particularly following thermal processing.

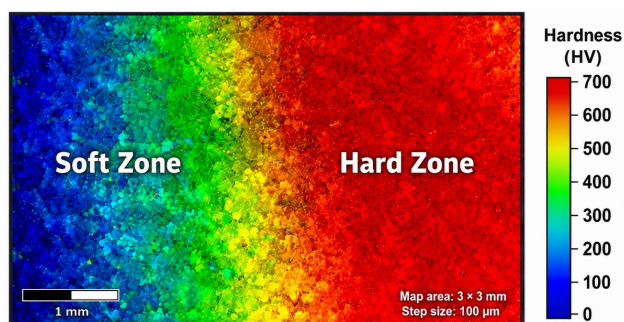


Fig. 11. Hardness map of St45 steel after heating at 900°C for 60 min and water cooling.

Note: The maximum measured hardness in the mapped area was approximately 610 HV0.1.

The hardness distribution shows how the sample's microstructure and phase composition vary spatially. The soft zones are mostly ferritic or ferrite-pearlite regions, whereas the hard zones are martensite-rich areas created by rapid water cooling; this is consistent with the phase distribution shown in the EBSD map. This variation in mechanical characteristics causes unequal resistance to deformation, promoting differential strain and contributing to the overall distortion of the metal elements. It should be noted that the hardness map and the EBSD map were obtained from specimens of the same steel grade under identical heat-treatment conditions, namely St45 steel heated to 900°C for 60 min and water-cooled. Although the maps were not acquired from exactly the same microscopic field of view, their spatial trends are consistent: regions of higher hardness correspond to martensite-dominated areas, whereas regions of lower hardness correspond to ferritic or more equilibrium-phase areas.

Rahman and Joy [39] showed that rapid phase transformation during quenching improves strength and hardness, but this enhancement is inevitably accompanied by the generation of large internal stresses that increase susceptibility to deformation. Annealing, in contrast, increases ductility and promotes stress re-

laxation, improving geometric stability at the cost of reduced strength [40]. This exemplifies a fundamental trade-off in heat treatment: treatments that stabilise geometry usually reduce the achievable strength level, whereas methods that improve mechanical performance tend to amplify thermal gradients and residual stresses. Similarly, Eryildiz *et al.* [41] demonstrated that, whereas annealing allows slow stress redistribution and reduces warping, rapid cooling during quenching produces strong thermal stresses and noticeable distortion. Collectively, these results demonstrate that selecting a heat treatment regime involves a trade-off between improving mechanical properties and maintaining dimensional accuracy, emphasising the need to tailor thermal parameters to the specific balance of permissible deformation and strength required for a given application. Mareau [42] proposed a constitutive modelling framework for metallic materials that incorporates thermo-mechanical coupling into material responses under non-isothermal conditions. Although this constitutive framework is not specific to quenching, it describes temperature-dependent plastic flow and elasticity in a manner directly applicable to heat-treated steels. Incorporating comparable constitutive formulations into quench-distortion analysis would provide a stronger foundation for comparing quenching and annealing results in future work.

Thus, the type of heat treatment has a significant effect on the stability of the configuration of metal elements. Understanding the specifics of each method, together with the use of experimental data, allows engineers and technologists to minimise deformation, increase product reliability, and improve production outcomes in both China and Kyrgyzstan.

3.5. Role of fixturing and fastening methods

One of the important factors affecting the accuracy of the shape and size of metal parts after heat treatment is the method used to fasten them in the furnace [43]. Under industrial conditions, metal elements may be placed freely in a thermal installation, rigidly fastened, or fixed using flexible retaining elements. Each of these methods has a different effect on the distribution of temperature and mechanical stresses during heating and cooling, and on the final residual deformation [44–46]. Free placement, despite its simplicity, is often accompanied by significant bending and warping of the product. This is conditioned by the effect of the component's own weight combined with uneven heating, especially in massive workpieces [47, 48]. According to experiments conducted at Osh Technological University (Kyrgyzstan), the residual deformation of free-lying samples with a thickness of 40 mm averaged 2.4 mm. Rigid fastening restricts the movement of the part during thermal exposure, thereby reducing the likelihood of curvature; however, it can create conditions for the accumulation of internal stresses, especially if the geometry of the product is complex. Under the same conditions, with rigid fastening, the residual deformation was 1.3 mm, almost half that observed under free placement.

The optimal result was achieved using flexible fastening (elastic, spring-loaded holders), which allows the part to move minimally in response to thermal expansion while maintaining the desired shape. The residual deformation did not exceed 0.9 mm. Table 12 shows the residual deformation values of 40 mm-thick St45 steel samples as a function of the fastening method, allowing assessment of the effect of workpiece fastening on reducing deformation during quenching.

Table 12

Residual deformation as a function of the fastening method (40 mm St45 steel samples).

Method of fastening	Average residual deformation (mm)
Unconstrained (no fastening)	2.4
Rigid fastening	1.3
Flexible fastening	0.9

Meena and Anant [49] demonstrated that, by governing the level of mechanical constraint applied to a component during thermal expansion and contraction, fastening conditions have a direct impact on deformation. Free thermal strain is restricted by rigid fastening, causing internal stresses to accumulate and eventually release as bending or curvature upon cooling [50–52]. Inadequate or absent fastening, in contrast, permits uncontrolled movement under non-uniform heat loading and self-weight, which can lead to substantial geometric deformation. Flexible fastening, as shown by An *et al.* [53], provides a controlled degree of compliance, allowing partial accommodation of thermal expansion while preserving positional stability. From a mechanical perspective, the reduced residual deformation shown in table 8 can be explained by this reduction in constraint, which limits stress concentration and promotes more uniform stress redistribution. Flexible fastening therefore offers a balanced mechanical state that minimises stress generation while maintaining geometric precision and operational reliability, particularly for elements with complex geometry or uneven heating [54, 55].

Thus, the fastening conditions used during heat treatment have a direct effect on the accuracy of the product geometry. The choice of method should be determined not only by the design features of the part but also by the requirements for accuracy, shape stability, and permissible internal stresses. This is particularly important for the production of parts in Kyrgyzstan and China, where thermal technologies are actively used in construction, mechanical engineering, and energy [56].

3.6. Synthesis and practical implications

The study found that the thermal heating regime has a decisive effect on the geometric stability of metal elements. Heating to 750, 850, and 900°C caused grain growth and phase transformations, leading to volume changes and local deformation, especially in samples thicker than 30 mm. Rapid water cooling generated internal stresses, causing bending and warping: for

St45 samples 400–500 mm long, the average residual deformation reached 2.4 mm. Oil cooling reduced deformation to 1.8 mm, and air cooling ensured minimal residual deformation of 1.2 mm. The geometric characteristics of the elements increased local overheating and deformation; at a thickness of 40 mm and above, residual deformation increased almost twofold compared with thin samples. The fastening method also significantly affected the results: without fastening, the average deformation was 1.2–2.0 mm; with rigid fastening, 1.8–2.5 mm; and with flexible fastening, 1.0–1.5 mm, which compensated for thermal expansion. The composition of the material determined the resistance to thermal deformation: alloyed steels containing chromium and molybdenum showed less deformation than the carbon-steel analogues under identical heating and cooling conditions. These quantitative relationships are supported by data from the laboratories of Osh Technological University and industrial enterprises in China. Thus, optimising the heating temperature, the cooling method, the fastening method, and the material, while taking into account the geometry of the elements, can significantly reduce residual deformation.

The novel contribution of this study is the quantitative evaluation of the heating temperature, cooling medium, fastening method, material composition, and element geometry within a single experimental framework, enabling the identification of useful deformation thresholds for industrial heat-treatment conditions. In contrast to previous research, which usually addresses these issues separately, the results offer experimentally validated parameter combinations that minimise residual deformation and are directly applicable to production settings. The results obtained are of practical importance for improving the accuracy and reliability of metal structures, and can serve as a basis for methodological recommendations on the heat treatment of elements with critical geometric-stability requirements. At the same time, the findings are limited by the range of steel grades and element dimensions investigated, and by the absence of direct microstructural characterisation, which may affect the extrapolation of the results to larger structures or other alloy systems.

4. Conclusion

This study provides a comprehensive analysis of how various heat treatment modes affect the geometric stability of metal elements, with particular focus on applications in Kyrgyzstan and China. Key contributions of this research include the quantification of the effects of heating temperature (750, 800, 850, 900, and 950°C), cooling method (water, oil, air, furnace), and fastening conditions on residual deformation and internal stresses. The results showed that rapid water cooling caused average residual deformation of 1.8–2.5 mm for samples 400–500 mm long; deformation decreased to 1.0–1.5 mm with oil cooling, 0.4–0.8 mm with air cooling, and 0.2–0.5 mm with slow furnace cooling. The study also highlights the significance of fastening methods, with flexible fastening producing the least deformation (0.9 mm), rigid fastening produc-

ing 1.3 mm, and no fastening producing up to 2.4 mm. These results are especially important for the construction, mechanical engineering, and energy sectors in Kyrgyzstan and China, where optimising heat treatment parameters can improve the accuracy of metal components.

The practical significance of the research lies in the possibility of using the data obtained for the development of technological data sheets, the selection of heat treatment modes, and fastening methods in the production of metal structures, thereby increasing accuracy and reducing the number of defects. A limitation of the study was the use of samples of limited size and specific steel grades. A further limitation is the small number of repetitions of the procedure, which may reduce the statistical robustness of the conclusions and introduce variability affecting the reliability of the results. With only three repetitions, the standard error of the mean is approximately 0.06–0.12 mm (based on observed variability), which may affect the detection of small differences (<0.2 mm) between experimental conditions.

Prospects for further research include studying the effect of heat treatment on large-scale elements, optimising modes for complex alloys, and developing models for predicting deformation based on multiparametric factors. The main outcome of this study is the establishment of quantitative relationships between heating temperature, cooling method, fastening method, and residual deformation, which can be applied for practical purposes and serves as a basis for further study of the large-scale effects of heat treatment on industrial structures.

Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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