
REDUCING COMPONENT DISTORTION BY IMPROVING THE MECHATRONIC SYSTEM OF HEAT TREATMENT EQUIPMENT

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Abstract

This paper examines ways of reducing residual stresses and distortion in metal components during heat treatment. Non-uniform temperature distributions, differences in heating and cooling rates, and phase transformations can impair the geometric accuracy of components. The paper considers improvements to the mechatronic system of heat treatment equipment, mathematical modelling of process parameters, and opportunities for optimal control. The proposed approach relies on coordinated operation of temperature monitoring, measurement instruments, the control algorithm, and actuators. The intended outcome is a technical solution for reducing component distortion and improving shape and dimensional stability.

Keywords: Heat treatment, mechatronic system, residual stress, component distortion, mathematical model, temperature field, optimal control, automation, optimisation.

1. Introduction

Heat treatment of metal components is widely used in mechanical engineering to improve mechanical properties, increase hardness and wear resistance, and extend service life. However, the thermal and microstructural processes occurring during heating, holding, and cooling can alter component shape and dimensions.

Distortion after heat treatment depends on several factors, including material properties, component geometry, initial temperature, heating and cooling rates, treatment duration, and the cooling medium. Their interaction produces temperature gradients and internal stresses within the component and, in some cases, residual distortion.

Conventional heat treatment equipment allows temperature and time to be monitored, but its capacity to adjust process parameters to the actual

condition of a component may be limited. Mechatronic solutions that integrate measurement instruments, controllers, and actuators into a single system offer a way to address this limitation.

The study focuses on establishing the scientific basis for controlling heat treatment parameters and reducing component distortion by improving the mechatronic system of the equipment.

2. Previous research

The prediction and reduction of heat treatment distortion have been widely investigated in international research.

In a study published in 2022, Shao and colleagues investigated distortion in 8620H steel gears caused by carburising and quenching, using numerical modelling and experimental verification. They analysed the effects of component design and cooling conditions on distortion and proposed a design modification to reduce it [1].

Monteiro and Cotton, in a study published in 2023, used the finite element method to model residual stresses induced by heat treatment in AA7075-T6 alloy. The calculated results were compared with experimental measurements to assess model reliability [2].

Mathematical modelling has also been used to investigate the relationships between induction hardening, heat transfer, phase transformations, and residual stresses. Such approaches allow temperature distributions, internal stresses, and potential component distortion to be estimated in advance [3].

Previous studies have made progress in modelling heat treatment and reducing distortion. The integration of the mechatronic system of a specific machine with measurement instruments, a mathematical model, and a control algorithm remains a possible direction for further research.

The present work therefore considers both the calculation of distortion and the use of the calculated results to control heat treatment parameters.

3. Research aim and objectives

The aim is to reduce residual component distortion and improve shape and dimensional stability by improving the mechatronic system of heat treatment equipment and optimally controlling thermal process parameters.

The following objectives are proposed:

1. Identify the main factors causing component distortion during heat treatment.
2. Analyse the mechatronic system and control parameters of the existing equipment.
3. Develop a mathematical model describing the relationships between temperature distribution, residual stress, and distortion.
4. Coordinate temperature measurement, data processing, and control functions.
5. Develop an optimal control algorithm aimed at reducing distortion.
6. Compare calculated results with experimental data and assess the effectiveness of the proposed solution.

4. Causes of distortion during heat treatment

Different regions of a component may heat or cool at different rates during treatment. This creates temperature differences between the interior and the surface, causing non-uniform thermal expansion and contraction.

Phase transformations in the metal may also produce volume changes. When these transformations proceed differently across the component, internal stresses become unevenly distributed. The resulting shape or dimensions may therefore differ from the initial geometry.

The main factors affecting distortion are:

- the component material and its temperature-dependent properties;
- component geometry and dimensions;
- heating rate and temperature distribution;
- holding time at the specified temperature;
- cooling rate and the properties of the cooling medium;
- phase transformations and the development of residual stresses;
- the temperature control accuracy of the equipment.

These factors must be considered together to assess distortion and develop a control strategy for reducing it.

5. Improving the mechatronic system

A mechatronic system combines mechanical devices, measurement sensors, control hardware, and software algorithms. In heat treatment equipment, this integration enables key process parameters to be monitored and, where necessary, adjusted to their specified values.

The proposed mechatronic system may comprise the following functional elements:

Measurement system. Suitable sensors and instruments are used to monitor the temperature of the component or the treatment chamber. Where required, measurements at several locations allow temperature non-uniformity to be assessed.

Data processing system. Measured temperatures and process parameters are processed digitally and supplied to the mathematical model to assess the current state of the process.

Control algorithm. The mathematical model and specified constraints provide the basis for selecting and coordinating the heating schedule, holding time, and cooling parameters.

Actuators. Elements affecting heating and cooling operate in response to commands from the controller.

Monitoring and analysis system. Process data are recorded, and calculated results are compared with experimental measurements to assess the effectiveness of the control solution.

Coordinated operation of these elements provides a basis for improving process repeatability and controlling the factors that cause distortion.

6. Mathematical modelling and problem formulation

A mathematical model can be used to assess how process parameters affect the condition of a component. It should account for heat transfer, spatial and temporal temperature variations, the mechanical properties of the material, and the development of residual stresses.

Model inputs include the component material, geometric dimensions, initial temperature, heating rate, holding time at the specified temperature, and cooling conditions.

The model is intended to estimate temperature distribution, residual stresses, and component distortion. The objective is to minimise distortion by selecting heat treatment parameters within the specified process and material constraints.

The general problem is to identify the heat treatment parameters that produce the lowest component distortion.

Parameter selection must also preserve the required hardness and other mechanical properties. Reducing distortion must therefore be considered alongside the process requirements for component quality.

Initial and boundary conditions are defined according to the initial state of the component, heating conditions, heat transfer, and the cooling medium. The reliability of the calculated results should be assessed by comparison with experimental measurements.

7. Proposed algorithm

The following algorithm is proposed for selecting heat treatment parameters and controlling them through the mechatronic system.

First, the component material, geometric dimensions, and initial heat treatment parameters are entered. A mathematical model of the thermal process is then formulated to determine the temperature distribution within the component.

The third stage calculates residual stresses and distortion from the temperature distribution and material properties. The calculated results are then analysed to select heat treatment parameters that may reduce distortion. At the fifth stage, the selected parameters are transferred to the mechatronic controller. Heat treatment is then carried out, and the resulting component condition is measured. Finally, the experimental results are compared with model predictions, and the model parameters are refined where necessary. The algorithm links mathematical modelling with practical control and experimental verification. Its ability to operate in real time, and the accuracy of control, depend on the capabilities of the sensors, computing hardware, and actuators.

8. Experiments and data validation

Experimental data from heat treatment are needed to assess model reliability. The dataset may include temperatures during heating and cooling, process duration, cooling conditions, material properties, and geometric measurements before and after treatment.

Data may be obtained from laboratory experiments, production trials, and verified computational results. The measurement conditions, units, and source of each data item should be recorded.

For model validation, it is advisable to use experimental data that are separate from those used for model calibration. This allows the reliability of predictions under new experimental conditions to be assessed, rather than evaluating only the fit to the original data.

The following indicators may be used for comparison:

- differences between calculated and measured temperatures;
- differences between calculated and measured distortion;
- measurement repeatability;
- time required for computation and control;
- geometric accuracy after heat treatment;
- the proportion of components that fail to meet requirements.

Numerical values for these indicators cannot be reported reliably until experimental results are available. The quantitative assessment of effectiveness must therefore be based on experimental and modelling results.

9. Expected technical and economic benefits

The main expected outcome of improving the mechatronic system is more precise control of heat treatment parameters and the factors influencing distortion.

If the proposed solution is verified experimentally, the following benefits may be achieved:

- reduced residual distortion after heat treatment;
- improved shape and dimensional stability;
- better process repeatability;
- less need for corrective work and reprocessing;
- lower costs associated with rejected components;
- greater capacity to monitor and control heat treatment.

Economic assessment should compare the proportion of rejected components, reprocessing costs, energy consumption, treatment duration, and equipment throughput before and after implementation. These comparisons would allow the benefits of the proposed mechatronic system under production conditions to be quantified.

10. Conclusion

Distortion of metal components during heat treatment is a complex problem associated with non-uniform temperature distributions, heating and cooling conditions, and phase transformations. Addressing it requires improvements to equipment design as well as measurement, modelling, and control functions.

This paper presents an approach to improving the mechatronic system of heat treatment equipment. It is based on using a mathematical model to assess the relationships between temperature distribution, residual stress, and distortion, select optimal process parameters, and apply them through the control system.

The practical value of the approach depends on experimental verification of the mathematical model and control algorithm, and on assessing their effectiveness using measurable indicators. This provides a basis for developing a technical solution to reduce component distortion, improve geometric accuracy, and increase the stability of the heat treatment process.

References

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