

Reducing Part Deformation by Improving the Mechatronic System of Induction Heat-Treatment Equipment

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Abstract

Induction heat treatment is used to improve the surface properties of machine parts, but nonuniform heating and cooling can produce residual stresses and dimensional changes. This paper proposes a mechatronic control concept for induction heat-treatment equipment to improve process consistency and reduce the risk of part deformation. A targeted review of published work is combined with a conceptual system design. The proposed architecture links temperature sensing, signal conditioning, a programmable controller, an adjustable induction power source, a workpiece-motion mechanism, and controlled quenching. Published confirmation-test data from an induction-hardening study are reanalyzed descriptively to illustrate how deformation measurements and process limits can inform monitoring. Across six reported tests, maximum deflection ranged from 605 to 815 μm , with a calculated mean of 694.2 μm ; these values belong to the cited study and are not results of the present design. The proposed system provides a practical framework for future implementation. Its effect must be confirmed on a defined workpiece through controlled experiments or validated simulation.

Keywords: Induction hardening; mechatronic system; temperature monitoring; adaptive control; part deformation; quenching.

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1. Introduction

Induction hardening is a localized heat-treatment process used to increase surface hardness and wear resistance while retaining the properties of the component core. An alternating electromagnetic field heats the selected region, and rapid cooling follows. The treatment zone and penetration depth depend in part on coil geometry and electrical operating conditions [1, 2]. Because heating and quenching occur over short time scales, small variations in workpiece position, power delivery, or cooling can alter the thermal cycle.

Dimensional change after heat treatment remains a practical manufacturing concern. During heating and quenching, temperature gradients and phase transformations produce strains and residual stresses. Their distribution depends on material composition, initial condition, geometry, section thickness, heating pattern, and quenching conditions [3, 4]. These influences interact, so reducing deformation requires attention to both the part and the process. A single fixed setting may not provide the same outcome when material or operating conditions vary.

Research on induction hardening has addressed process simulation, parameter sensitivity, and optimization. Coupled electromagnetic, thermal, and mechanical models are used to examine stress and deformation [4, 8, 9]. Sensitivity studies and optimal-control and hybrid-modeling approaches have also been used to examine or optimize process conditions [5–7]. These methods show that process behavior can be studied through measurements and models, but their implementation requires adequate process data and calibration.

A mechatronic approach can connect sensors, controllers, and actuators so that the treatment cycle responds to measured conditions. For induction heat-treatment equipment, relevant variables may include heating power, coil-to-workpiece gap, workpiece feed or rotation, and quench flow or temperature. In an industrial rack-bar case, power and feed rate were important terms in the reported maximal-deflection model, while the coil gap had a smaller contribution under that study's specific conditions [10]. This evidence supports monitoring several parameters together rather than relying on heating power alone.

This paper develops a practical conceptual design for improving the mechatronic system of induction heat-treatment equipment. Its objective is to describe a feedback arrangement that monitors temperature and process status and adjusts selected operating parameters to promote a more consistent thermal cycle. The paper also presents descriptive statistics calculated from published confirmation-test measurements. These secondary data illustrate how deformation thresholds and process-variable effects can be reported; they do not evaluate the proposed system.

The contribution is therefore twofold: a simple control architecture is proposed for future equipment improvement, and a published data set is summarized to demonstrate how statistical indicators can support process monitoring. The design is intended as a starting point for a defined machine and workpiece. Experimental validation remains necessary before any quantitative reduction in deformation can be claimed.

2. Methods

2.1. Study design and source selection. The study follows a design-oriented, conceptual approach. It combines a targeted review of literature on quench distortion, induction hardening, process modeling, and control with the development of a proposed equipment

architecture. The cited sources were selected for their direct relevance to deformation mechanisms, induction-heating control, or measured process optimization. The review is not presented as a systematic review, and no claim is made that it exhausts all publications on the topic.

The proposed control concept is formulated at equipment level. It identifies measurable process inputs and outputs, specifies how the controller may respond to deviations, and distinguishes monitored variables from control actions. No physical prototype was constructed and no new heat-treatment experiment was conducted for this paper.

2.2. Secondary data and statistical treatment. For an illustrative statistical analysis, six maximum-deflection measurements reported in the confirmation experiments of Dziatkiewicz et al. [10] were transcribed from the published table. The measurements were 605, 815, 773, 681, 656, and 635 μm . The source study treated 1,000 μm as the upper limit for maximum deflection before the subsequent production stage. The six values are retained as published; descriptive statistics were calculated here to summarize their distribution.

The arithmetic mean, median, sample standard deviation, minimum, maximum, and range were calculated. The share of observations below the stated 1,000 μm limit was also determined. Because the sample is small and comes from one component and one industrial process, these summaries are illustrative and should not be generalized to other parts or equipment.

2.3. Proposed mechatronic system. The proposed architecture includes a temperature-measurement unit, signal-conditioning and data-acquisition functions, a programmable logic controller or microcontroller, a controllable induction power source, a workpiece-motion drive, and a quenching unit. A temperature sensor suited to the machine environment provides process feedback. Additional sensors may monitor workpiece position, rotational or feed speed, quench-fluid temperature, and flow status where the equipment permits.

The controller compares the current process state with a recipe or target profile. When a deviation exceeds a configured tolerance, the controller can modify induction power, feed or rotation speed, or quench actuation within validated operating limits. Interlocks should stop or hold the cycle if a critical sensor signal is missing, the

workpiece is incorrectly positioned, or cooling is unavailable. The system must preserve the material-specific treatment requirements; lowering deformation cannot be pursued at the cost of inadequate hardness or case depth.

The design is intentionally modular. A basic implementation may monitor temperature and power while retaining existing motion and quench hardware. A more complete implementation can coordinate all actuators through a common controller. This staged arrangement allows the concept to be adapted to equipment capability and available measurements.

2.4. Process indicators. The principal quality indicator proposed for validation is maximum post-treatment deflection, measured at consistent locations with a calibrated displacement instrument. Supporting indicators include hardness, effective hardening depth,

and the repeatability of the temperature-time cycle. Input variables should include power setting, coil gap, feed or rotation speed, and quench conditions. Recording both quality responses and process inputs is necessary to determine whether a control change reduces deformation without degrading the required metallurgical properties.

3. Results

3.1. Proposed system architecture and operating sequence. Figure 1 presents the proposed feedback architecture. The sensing unit observes the thermal state and equipment status. Signal conditioning and data acquisition prepare these measurements for the controller. The controller applies the selected treatment recipe and sends commands to the induction source, the workpiece-motion drive, and the quenching unit. The resulting process state is measured again, closing the feedback loop.

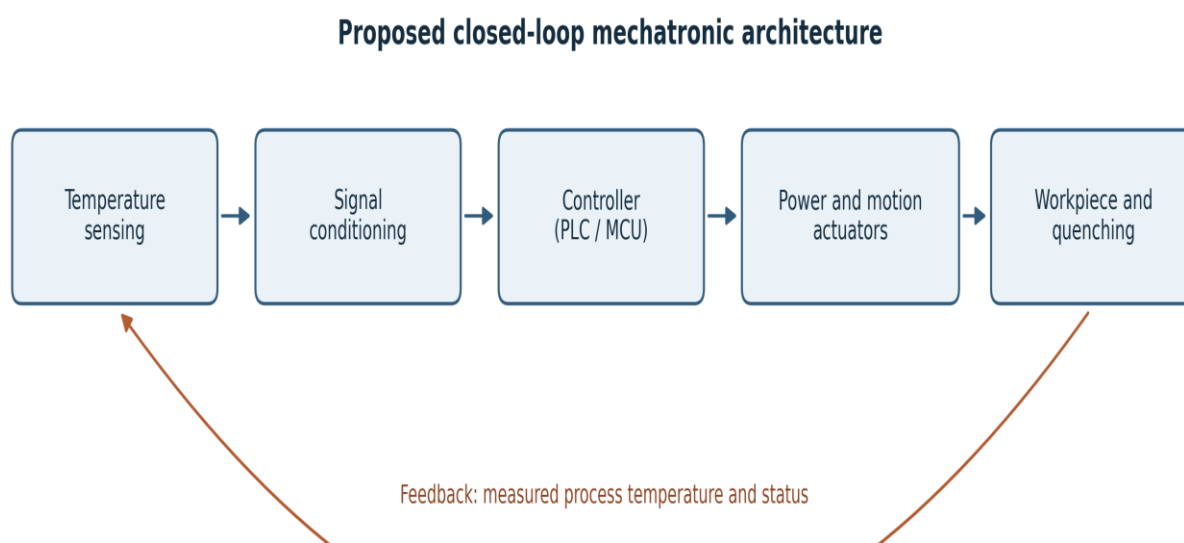


Figure 1. Conceptual closed-loop architecture proposed for induction heat-treatment equipment.

A practical cycle begins with verification of the workpiece and recipe. The controller checks sensor availability and confirms the initial position. During heating, it monitors temperature and the relevant actuator states. If a deviation occurs, it adjusts an available control variable within the allowed process window. During quenching, it verifies that the required cooling command is active. At the end of the cycle, the system stores the process record together with the part identification and measured quality result, where such measurement is available.

For initial implementation, the most useful data record would include time, measured temperature, power command, coil gap, feed or rotation speed, quench-fluid temperature, and flow status. Post-treatment deflection and hardness results can then be linked to the recorded cycle. This record would allow the process window to be refined using evidence from the actual equipment rather than transferring settings directly from another component.

3.2. Literature evidence relevant to equipment

control. The reviewed sources describe complementary parts of the problem. Work on distortion explains the role of thermal gradients, transformation strains, and quench conditions [3, 4]. Optimal-control and hybrid-modeling studies show ways to link process models with measured

or controlled heating conditions [5, 6]. More recent induction-hardening studies examine deformation prediction and parameter optimization for specific components [8–10]. Table 1 summarizes this evidence and its relevance to the proposed design.

Table 1. Selected literature and its relevance to the proposed mechatronic system

Source	Main focus	Relevance to this paper
Canale and Totten [3]	Factors affecting quench distortion and residual stress	Identifies process and material factors that must be considered together.
Favennec et al. [5]	Optimal control of induction-heating processes	Supports the use of process models and controlled operating conditions.
Asadzadeh et al. [6]	Hybrid model using physical knowledge and observations	Shows how measured data can complement a process model.
Dziatkiewicz et al. [10]	Industrial parameter optimization and confirmation tests	Provides published deformation measurements and process statistics.
Pinheiro et al. [8]; Hwang et al. [9]	Simulation of gear deformation and multiphysics deformation prediction	Supports future simulation-based assessment of a defined component.

The studies do not establish one universal setting for reducing deformation. Instead, they show that the relevant parameters depend on the workpiece and process. The control system should therefore use a validated recipe for the selected material and geometry, then monitor whether the machine follows that recipe.

3.3. Descriptive statistics from published confirmation tests. The six published confirmation

measurements range from 605 to 815 μm . Their calculated mean is 694.2 μm , median is 668.5 μm , and sample standard deviation is 82.3 μm . All six measurements fall below the 1,000 μm limit stated for the rack-bar process in the source study [10]. The mean is 30.6% below that limit; this is a margin relative to the specified limit and must not be interpreted as a 30.6% reduction from an untreated or baseline condition.

Table 2. Published maximum-deflection measurements and descriptive summary

Measure	Maximum deflection (μm)	Interpretation
Confirmation test 1	605	Published measurement
Confirmation test 2	815	Published measurement
Confirmation test 3	773	Published measurement
Confirmation test 4	681	Published measurement
Confirmation test 5	656	Published measurement
Confirmation test 6	635	Published measurement
Mean	694.2	Calculated from six published values
Median	668.5	Calculated from six published values
Sample standard deviation	82.3	Calculated with $n - 1$ in the denominator
Minimum–maximum	605–815	Range = 210 μm
Process limit	1,000	Limit reported for the source rack-bar process [10]

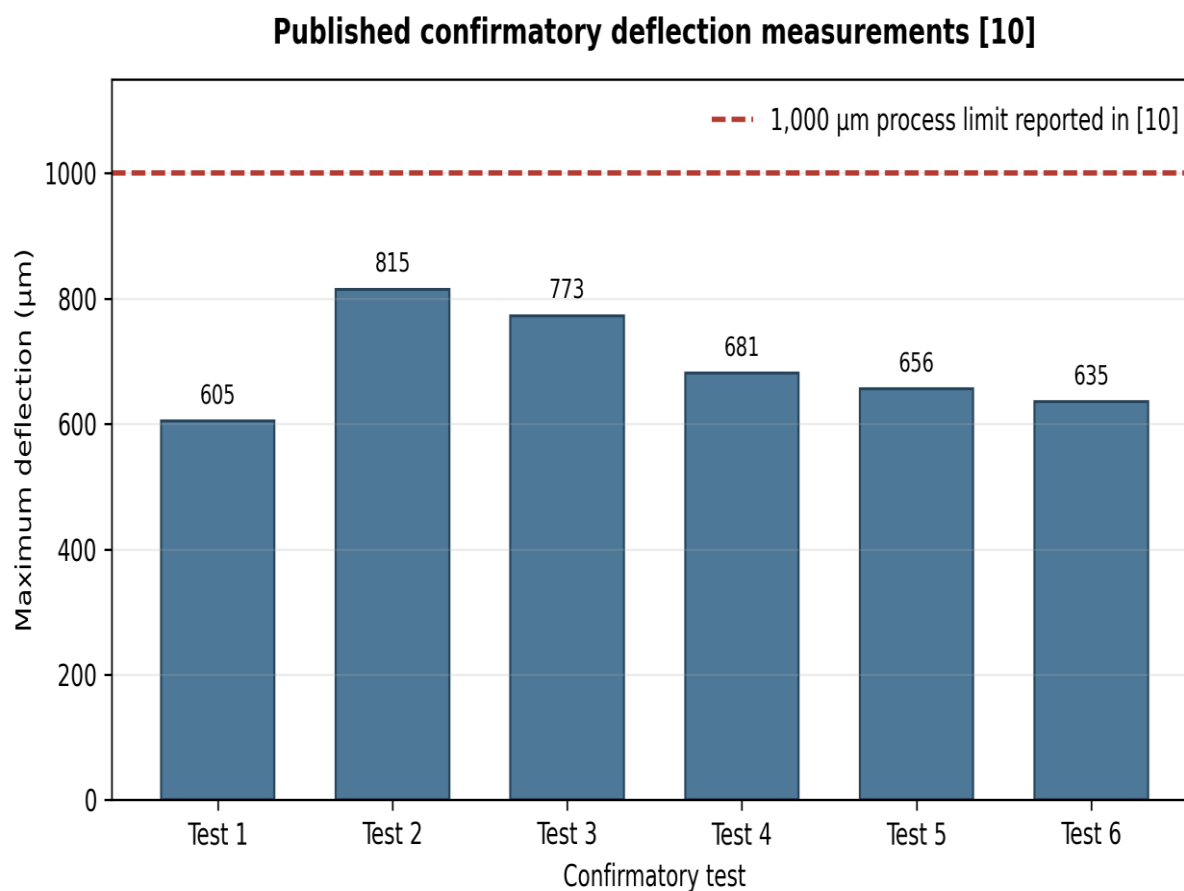


Figure 2. Maximum deflection in six published confirmation tests

3.4. Statistical contribution of process factors in the source model. The analysis of variance reported for the source study's maximal-deflection response model attributed 31.271% of the total sum of squares to power, 21.163% to feed rate, 14.054% to the power-by-feed-rate interaction, and 11.193% to the quadratic power term.

Their reported p-values were below .05. The coil-gap term contributed 0.411% and had a reported p-value of .638 in that model [10]. These values describe the fitted model and experimental design in the cited rack-bar study; they are not universal sensitivity coefficients.

Table 3. Selected terms in the published ANOVA model for maximum deflection

Model term	Contribution (%)	p-value	Reported interpretation
Power	31.271	.002	Statistically significant in the source model
Feed rate	21.163	.006	Statistically significant in the source model
Power × feed rate	14.054	.018	Statistically significant interaction
Power²	11.193	.030	Statistically significant quadratic term
Coil gap	0.411	.638	Not statistically significant in the source model

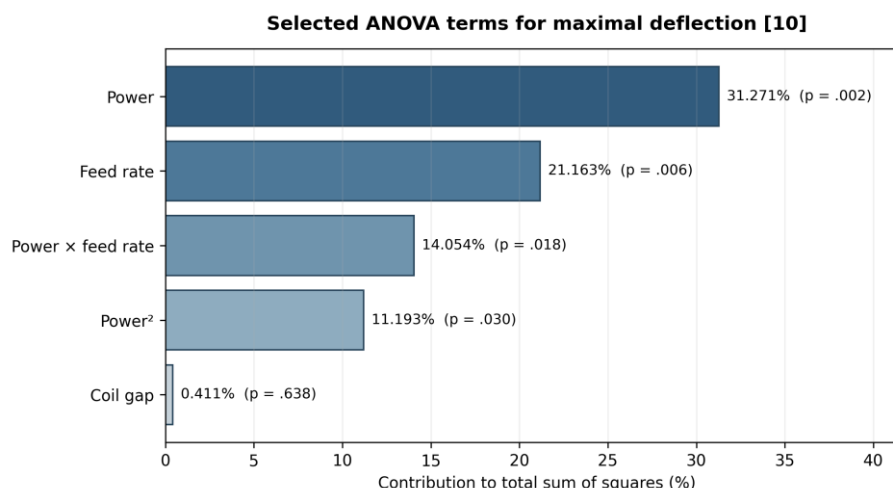


Figure 3. Selected factor contributions to the published maximum-deflection model

4. Discussion

4.1. Why feedback is relevant. The literature and the secondary data analyzed here support the use of process monitoring, but they do not prove the effectiveness of the proposed system. The published rack-bar study shows that deformation and hardness requirements can be considered together during parameter optimization [10]. It also demonstrates why control settings must be judged against multiple quality criteria: the setting with the highest combined desirability was not adopted as the final industrial setting because of practical equipment considerations. A mechatronic upgrade should therefore preserve constraints related to hardness, case depth, cycle time, and equipment limits.

The proposed feedback loop is intended to reduce variation between the prescribed and actual process cycle. If the measured thermal state departs from the target, the controller can respond while the part is still being treated. This may be more useful than a purely open-loop recipe when disturbances or part-to-part variation occur. However, temperature measurement alone cannot represent every source of distortion. Material variability, initial stresses, geometry, and transformation behavior remain relevant [3, 4].

4.2. Interpretation of the statistical example. The six confirmation measurements in Table 2 provide an example of how a deformation limit can be assessed using measured values and summary statistics. All six values are below the 1,000 μm criterion reported for that rack-bar application [10]. The calculated average margin is 305.8 μm . This does not establish that the proposed mechatronic system would reduce deformation by that

amount. The measurements were obtained in a separate study under its own process conditions and are included here only as published evidence.

The source ANOVA results also show that parameter effects are context dependent. In the cited model, power and feed rate contributed more than coil gap to the modeled maximum deflection. Yet the authors report a significant lack of fit, which limits interpretation of the regression model [10]. For a new machine, a small pilot design of experiments or a validated simulation should determine which variables matter most. The source values should not be copied directly as a recommended operating recipe.

4.3. Practical implementation considerations. Sensor selection and placement are central to implementation. The measurement should represent the part region that governs the required treatment, and the sensor must function reliably in the electromagnetic, thermal, and mechanical environment of the equipment. The measured signal should be checked against an independent reference during commissioning. Controller sampling frequency, filtering, and alarm thresholds should be matched to the speed of the heating cycle.

The control logic should use bounded adjustments. A controller should not increase or decrease power without regard to metallurgical requirements. Likewise, changes in feed speed or quenching must be limited to ranges that preserve the required hardness profile and treatment depth. Any adaptive function should begin with a validated baseline recipe and keep traceable records of the changes it applies.

A staged upgrade may be more practical than replacing

all equipment controls at once. First, the machine can be instrumented to collect temperature and operating data. Second, the measurements can be compared with post-treatment dimensional and hardness results. Third, closed-loop adjustment can be enabled for one or two high-impact variables. This sequence reduces implementation complexity and provides evidence for later expansion.

4.4. Validation plan. The next stage should test the proposed system on one defined component and material. The validation plan should specify the baseline equipment settings, number of repeated parts, measurement locations, dimensional instrument accuracy, hardness and case-depth requirements, and the control variables to be adjusted. Deformation should be reported before and after improvement using the same measurement procedure. Temperature histories and process settings should be stored for each part. If simulation is used, it should be compared with measurements before it is used to predict deformation beyond the tested conditions [8, 9].

A simple comparison could report mean deflection, standard deviation, range, and the proportion of parts meeting the dimensional requirement for both baseline and controlled operation. Inferential statistics should be selected according to sample size and distribution. This would allow a future empirical paper to distinguish a measurable improvement from ordinary process variation.

4.5. Study limitations. This paper presents a conceptual system and a descriptive reanalysis of published measurements. It does not include a newly built prototype, an experiment on local equipment, or an independently validated thermal-mechanical model. The secondary data come from one rack-bar application and cannot establish expected performance for gears, shafts, or other components. The proposed architecture must therefore be adapted and validated for the selected equipment, material, part geometry, and treatment specification.

5. Conclusion

A feedback-based mechatronic system is proposed for induction heat-treatment equipment. It connects temperature and process monitoring with control of induction power, workpiece movement, and quenching. The purpose is to improve process consistency and create the conditions for reducing part deformation while

maintaining the required hardness and treatment depth.

A descriptive analysis of six published confirmation measurements produced a mean maximum deflection of 694.2 μm , a median of 668.5 μm , and a sample standard deviation of 82.3 μm . All six values were below the 1,000 μm process limit reported for the source rack-bar application [10]. These are secondary data and do not measure the performance of the proposed design.

The proposed system should next be evaluated on a defined machine and workpiece using repeated baseline and controlled trials. The validation should measure both dimensional change and metallurgical quality. Only after this testing can the reduction in deformation be quantified.

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