Induction hardening of gearwheels made from 42CrMo4 hardening and tempering steel by employing water-air spray cooling

Project A3 IRTG 1627 „Virtual Materials and Structures and their validation“
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Induction hardening

Principle
- Hardening of the surface layer
  - Heating for ferrite-austenite transformation
  - Rapid cooling for martensite formation
  - Heating duration of 0.1 s to 1 s
  - No phase transformation in the core

Advantages
- Energy saving
- Increase of wear resistance and fatigue strength
- Minimization of size changes
- Reduction of post-hardening machining

Time-temperature profiles during induction hardening
Induction heating by simultaneous dual frequency method

**Working principle**
- Simultaneous transmission of two oscillating electromagnetic fields to a component surface layer
- Tooth crest region: high frequency (HF) of 150 kHz to 350 kHz for hardening depths of 0.3 mm to 1 mm
- Tooth root region: middle frequency (MF) of 10 kHz to 25 kHz for hardening depths up to 2 mm

![Heating by an inductor](image)

![Induction heating with MF](image)  ![Induction heating with HF](image)

A: Inductor current (HF, MF)  
B: HF-, MF-currents in the workpiece  
C: Heating of tooth crest by HF and of tooth root by MF  
σ: Current penetration depth

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Quenching

State of the art
- Induction hardening by employing water-polymer solutions
  - Soft spot formation
  - Complicated handling
  - Bad skin compatibility of polymer solutions

Alternative
- Substitution of water-polymer quenching by water-air spray cooling
  - Water-air spray cooling
    - Good controllability of the quenching process
    - Self-tempering (tempering from the residual heat)
  - Renunciation of polymer-solution
    - Environmental compatibility
    - Cost saving
  - Low distortion
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Problem definition

Motivation
- Complicated handling of the quenching process by water-polymer solutions
- High procurement and disposal costs of polymer-solutions
- Need of an economic quenching method with high controllability
- Until now engineering of spraying fields is based on empirical investigations

Spraying field concept for induction hardening machine
Project objectives

- Integration of water-air spray cooling in the process of induction hardening
- Numerical model of induction hardening by water-air spray cooling
  - Consideration of thermal, microstructural and mechanical interactions
- Model implementation in commercial simulation software ANSYS Workbench 13.0
  - Macros in Ansys Parametric Design Language (APDL)
- Simulation results verification by experiments
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Experimental setup and test workpiece

Sprayfield
- Variability of nozzle number from 6 to 12
- Water and air pressure adjustable from 0.1 MPa to 0.6 MPa
- Variability of distance between the workpiece and the nozzles
- Control by an industrial PC using LabView

Spur and helical gearwheels of 42CrMo4
Induction hardening by employing spray cooling
Experimental results

Macrograph of induction hardened gearwheel by employing spray cooling

Hardness profiles in the tooth crest

Residual stresses

Distortion

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Cost analysis of the quenching process

Machine-related overhead costs in €/a

- calc. depreciation
- calc. interest
- room costs
- energy costs
- maintenance and repair costs

Machine-hour schedules
- Spray field approx. 4 € → 0.0078 €
- Polymer sprinkler approx. 5 € → 0.01 €
Self-tempering (tempering from the residual heat)

Tempered martensite in the tooth crest

Residual stresses

Furnace tempering

Distortion

Self-tempering

Hardness profiles in the tooth crest
Model-relevant processes

Induction heating

Temperature

Quenching by water-air spray cooling

1. Temperature
2. Microstructure
3. Residual stresses
4. Hardness
5. Distortion

1. Temperature induced phase transformation
2. Transformation heat
3. Thermal stresses
4. Deformation heat
5. Transformation stresses
6. Stress induced transformation
Temperature profile approximation after heating
## Verification of heating simulation results

<table>
<thead>
<tr>
<th>Point</th>
<th>EXP [°C]</th>
<th>FEM [°C]</th>
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</thead>
<tbody>
<tr>
<td>Point 1</td>
<td>828.60</td>
<td>831.91</td>
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<td>Point 2</td>
<td>726.40</td>
<td>724.24</td>
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<td>Point 3</td>
<td>599.50</td>
<td>615.20</td>
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<tr>
<td>Point 4</td>
<td>999.50</td>
<td>854.56</td>
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<td>Point 5</td>
<td>414.70</td>
<td>369.47</td>
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<tr>
<td>Point 6</td>
<td>56.90</td>
<td>44.38</td>
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### Simulated surface temperature

![Simulated surface temperature](image1.png)

### Measured surface temperature

![Measured surface temperature](image2.png)
Modelling of austenite formation

Volume fraction of austenite for different heating rates [Miokovic et al. 2006]

\[ F_A = a \cdot T^7 + b \cdot T^6 + c \cdot T^5 + d \cdot T^4 + e \cdot T^3 + f \cdot T^2 + g \cdot T + h \]

\[ R^2 = 0.9991129453 \]
Modelling of spray cooling

Temperature dependent heat transfer coefficients during quenching [Krause et al. 2008]

Temperature development during cooling
Verification of cooling simulation results

Point 1

Point 2

Point 3

Point 4

Point 5

Point 6
The Koistinen-Marburger equation:

\[ \xi_M = 1 - \exp[-k(M_s - \theta)] \]

- \( \xi_M \) - martensite fraction
- \( k \) - constant related to steel composition
- \( M_s \) - martensite starting temperature
- \( \theta \) - temperature

TTT-diagram of 42CrMo4 steel for continuous cooling

[Werkstoffdatenblatt 42CrMo4 (1.7225) 2010]

Model assumption

- No diffusional phase transformation
Modelling of hardness

\[
HV = \frac{a}{1 + b \cdot F_M + c \cdot F_M^2}
\]

\[
R^2 = 0.9971003333
\]

Relationship between the hardness and the martensite fraction [Nürnberg 2010]

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
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<tbody>
<tr>
<td>a</td>
<td>324.878598</td>
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<tr>
<td>b</td>
<td>-0.00862882</td>
</tr>
<tr>
<td>c</td>
<td>3.24E-05</td>
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</table>
Verification of hardness simulation results

Schematic of hardness measurements

Depth Tooth crest

Depth Tooth flank

Depth Tooth root

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Modelling of residual stresses and distortion

Elastic-plastic model

\[ (\varepsilon_{ij})^{tot} = (\varepsilon_{ij})^{el} + (\varepsilon_{ij})^{pl} + (\varepsilon_{ij})^{th} + (\varepsilon_{ij})^{tr} + (\varepsilon_{ij})^{tp} \]

- \( (\varepsilon_{ij})^{tot} \): total strain
- \( (\varepsilon_{ij})^{el} \): elastic strain
- \( (\varepsilon_{ij})^{pl} \): plastic strain
- \( (\varepsilon_{ij})^{th} \): thermal strain
- \( (\varepsilon_{ij})^{tr} \): transformation induced strain
- \( (\varepsilon_{ij})^{tp} \): transformation induced plasticity

Model assumptions

- Low deformation heat
- No stress induced transformation

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Conclusion/Outlook

Conclusion
- Substitutionability of water-polymer quenching by water-air spray cooling in the process of induction hardening was proved
  - Economic analysis of the quenching process
  - Self-tempering by employing spray cooling
- Model describing the quenching process by water-air spray cooling after induction heating was presented
  - Consideration of thermal, microstructural and mechanical interactions
- Simulation results were verified by experiments

Outlook
- Wear resistance and fatigue strength behaviour
- Modelling of self-tempering
Thank you for your attention!
References


References


Werkstoffdatenblatt 42CrMo4 (1.7225). Dr. Sommer Werkstofftechnik GmbH, Anwendungsinstitut zur Einsatzoptimierung von Werkstoffen, Verfahren, Wärmebehandlung, Issum, 2010