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Investigation of the surface residual stresses in spray cooled induction hardened gearwheels

Dedicated to Prof. Dr.-Ing. Christina Berger on the occasion of her 65th birthday

The objective of the current investigation consists of testing the interchangeability of polymer solutions used during induction hardening with water–air spraying regarding compressive residual stresses. Gearwheels made of 42CrMo4 steel were induction hardened and subsequently quenched using water–air spray cooling. The effect of different cooling parameters on the surface’s residual stresses in the gearwheel’s tooth flanks was analysed by means of X-ray diffraction. The microstructure was characterised by means of hardness measurements and light-microscopy. Residual stresses could be specified after using water–air spray cooling and are comparable to those using polymer quenching. Quench parameters leading to maximum compressive residual stresses in tooth flanks were determined.

Keywords: Water–air spray cooling; Induction hardening; Surface residual stresses; Microstructure

1. Introduction

Locally specified strength properties in component regions, such as gear teeth, which correspond to their loading stresses, can be realised by means of inductive surface hardening. Based on the skin-effect, the component’s surface layer is rapidly austenitised followed by subsequent quenching. The treatment’s advantage is that the hardening process is concentrated in the surface region whereby any distortions which result from the volume changes caused by heating and phase transformations are minimised [1]. One of the quality objectives of induction hardening is to achieve compressive residual stresses in the component’s subsurface regions, which favourably affects the fatigue properties. In contrast to tensile residual stresses, compressive stresses oppose the initiation and growth of cracks which reduce the component’s service life [2]. They elevate the fatigue loading capacity and protect the surface from the effect of notches, inclusions and corrosion pits. Compressive residual stresses have a retarding effect on stress and fatigue crack corrosion [3]. The magnitude and sign of the residual stresses which arise following hardening are essentially determined by the pre-processing state as well as the heating and the quenching conditions. The latter are defined by the choice of the quenching medium. The quenching mediums conventionally used for inductive surface hardening are polymer solutions. Their cooling characteristics lie between those of water and oil emulsions. The temperature profile during quenching, and thus the resulting hardness values, is determined by the polymer solution’s concentration, the temperature and the polymer solution’s volumetric flow rate [4]. For economic reasons, the polymer solution is recycled in a closed flow loop and its chosen concentration needs to be regularly monitored. Owing to the polymer solution’s repeated use, contaminants from the components, such as coolants and processing oils, enter into quenching medium. Thus, the resulting hardening is impeded [5]. By substituting an ecological water–air spray for the polymer solution, the problem of the polymer solution’s costly maintenance and disposal is eliminated. In comparison with polymer solutions, quenching can be chronologically and spatially controlled by means of water–air spraying. This has been confirmed in investigations on CK45 steel cylinders by Moreaux et al. [6]. The authors employed water, atomised by air, to quench the surface layer of induction heated specimens. Evaluation of the measured temperature and hardness profiles demonstrated that it is possible to uniformly quench by means of spray cooling. Rodman et al. [7] have combined the induction heating process, according to the simultaneous dual frequency method, with quenching using water–air spray cooling by integrating a spraying device into 3 MW induction heating equipment. Gearwheels made of 42CrMo4 hardening and tempering steel, which are induction hardened in this way, were assessed by using hardness measurements, microstructural examination and changes in dimensions and geometry. A comparison with gearwheels which were induction hardened using a polymer solution showed that an analogous microstructure to polymer quenching can be realised using water–air spray cooling. In addition to this, corresponding hardness profiles can be obtained for comparable changes in dimension and geometry.

The aim of the investigations carried out consisted of determining the quenching parameters which lead to high compressive residual stresses homogeneously distributed across the tooth flanks. The motivation was to generate specific magnitudes of residual stress, which are obtained with polymer quenching, in order to demonstrate the interchangeabili-
ity of the latter with regard to the controlled specification of residual stresses. For this purpose, the influence of quenching parameters on the residual stresses was investigated for water–air spray cooling by means of X-ray diffraction.

2. Experimental procedure

Gearwheels made of 42CrMo4 (1.7225) hardening and tempering steel, were used for carrying out the investigations. The spur gearwheels had 28 teeth and a gear module of 2.6. They were manufactured by machining and subsequently heat-treated to specify the core’s microstructure. The chemical composition of the gearwheel’s material can be found in Table 1.

The gearwheels were induction hardened using 3 MW testing equipment made by the company elec Schwenk Induction GmbH with an integrated spray field or, as the case may be, a conventional polymer sprinkler. The test set-up (Fig. 1) is described in more detail by Rodman et al. [7].

The quench temperature was approximately 900 °C at a high frequency (HF) power of 420 kW and a middle frequency (MF) power of 405 kW. Heating took place within 0.2 s and quenching was carried out using an 8% polymer solution within 15 s at pressures of 0.2 MPa and 0.3 MPa. As an alternative to this, the cooling was performed with a quench delay of 20 s and then using a pressure of 0.2 MPa. The polymer solution’s temperature was 25 °C. Six high pressure, two-component nozzles (type 1/8JIAU) made by the company Spraying Systems were employed for the water–air spray cooling. They were composed of an air-jet (model 1/8JJPAJ173160) and a nozzle for liquids (model 1/8JJPF12850). The water pressures were varied from 0.1 MPa to 0.5 MPa at a constant air pressure of 0.3 MPa (Table 2).

The water pressures were chosen between 0.3 MPa and 0.5 MPa for air pressures of 0.4 MPa and 0.5 MPa since water at low pressures is suppressed by the air [8]. The water temperature was 20 °C. Gas quenching was performed using compressed air at pressures of 0.3 MPa and 0.6 MPa. Quenching took place within 30 s. To provide homogeneous induction heating and uniform cooling, the gearwheels were rotated at 1000 rpm and 25 rpm, respectively. Reducing the rotation speed for the quenching phase is justified since, at high rotational speeds, the quenching medium is not retained on the component’s surface. As a consequence, a non-uniform hardening is produced and thus soft spots are formed [9]. Subsequent to the hardening treatment, the gearwheels were tempered at a temperature of 180 °C for 90 min.

![Induction hardening machine](image1)

![Spray field control](image2)

**Fig. 1.** Induction hardening equipment with the integrated spray field.

Table 1. Chemical composition of the gearwheel material 42CrMo4 determined by means of glow-discharge spectroscopy (data in weight percent).

<table>
<thead>
<tr>
<th>C</th>
<th>Mn</th>
<th>Si</th>
<th>S</th>
<th>Cr</th>
<th>Mo</th>
<th>P</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.422</td>
<td>0.653</td>
<td>0.284</td>
<td>0.027</td>
<td>1.031</td>
<td>0.149</td>
<td>0.009</td>
<td>96.978</td>
</tr>
</tbody>
</table>

Table 2. Quenching parameters of the water–air spray cooling, the gas and the polymer cooling.

<table>
<thead>
<tr>
<th>Water–air spray cooling</th>
<th>7</th>
<th>30</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air pressure (MPa)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.3</td>
<td>0.4</td>
</tr>
<tr>
<td>Water pressure (MPa)</td>
<td>0.0</td>
<td>×</td>
</tr>
<tr>
<td>Quench duration (s)</td>
<td>15</td>
<td>20</td>
</tr>
<tr>
<td>Quench delay (s)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Polymer pressure (MPa)</td>
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</tbody>
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Individual teeth were removed from the gearwheel by means of wire spark erosion for the residual stress measurements. Analysis was performed on the tooth flanks' surfaces at the Institute of Production Engineering and Machine Tools, Leibniz Universität Hannover using a 2-circle X-ray diffractometer (type XRD 3003 T/T) made by General Electric. The surface residual stresses were determined using the Philips method according to Mächler and Muller [10].

For this analysis, the diffractometer was equipped with a Ni-filtered Cu-Kα radiation and a position sensitive detector. To avoid drift, a Pb-scintillator collimator was used. Measurements were taken on the hkl 211 lattice plane of α-Fe, in which the maximum penetration depth of the X-ray beam is \( \tau_{\text{max}} = 5.5 \, \mu\text{m} \). The X-ray diffractometer’s stress measuring accuracy is given by the manufacturer as \( \pm 10 \, \text{MPa} \). Two measurements per tooth flank were performed, and the mean of these was calculated.

Using a wet cutting-wheel, gearwheel segments consisting of 3 teeth were prepared for the hardness measurements and the light-microscopy examinations. For the hardness measurements, the respective specimens were ground and polished to a 3 \( \mu\text{m} \) surface finish. The light-microscopy analysis required a polished surface finish to 1 \( \mu\text{m} \) and a subsequent etch with 2 \% nitric acid. The depicted hardness values were each formed from the mean value of 3 measurements.

3. Results

3.1. Hardness and microstructure

Prior to induction hardening, the gearwheel’s microstructure and the hardness values were investigated in the region of the tooth flanks. The metallographic analysis revealed a heat treated microstructure consisting of ferrite and cementite precipitates (Fig. 2). The measured hardness values lay in the range from 325 HV0.5 to 348 HV0.5. The specified heat treated microstructure represents good preconditions for induction hardening since it favours the concentration-exchange for carbon and other alloying elements by means of short diffusion paths. In this way, the austenitising process is accelerated [11].

Subsequent to induction hardening using a polymer solution, a hardness value in the range between 700 HV0.5 and 750 HV0.5 was measured for the pressures 0.2 MPa and 0.3 MPa (Fig. 3). The quench delay with a subsequent pressure of 0.2 MPa leads to a maximum hardness value of approximately 660 HV0.5. For simplicity, a polymer pressure of 0.2 MPa will be referred to as 0.2 WP in the following. QD (cf. Fig. 3) denotes the quench delay. The hardening depth determined according to DIN EN 10 328 is 0.5 mm and can be observed in Fig. 3 as a significantly narrower hardened region compared to quenching without a delay. The hardening depth in the region of the tooth flank is 0.82 mm and 0.9 mm for pressures of 0.2 MPa and 0.3 MPa, respectively.

As an example for the spray cooling, the abbreviation 0.3A-1.4W is used for the parameters 0.3 MPa and 0.4 MPa air and water pressures, respectively. The hardness value obtained in the region of the tooth flank using spray cooling is approximately 700 HV0.5. Figure 4a depicts examples of the hardness profiles for the pressure 0.3 MPa and water pressures in the range 0.1 MPa to 0.5 MPa. It is apparent that raising the water pressure at constant air pressure leads to displacement of the hardened zone to higher values. The hardening depth obtained in the region of the tooth flank using the spray cooling lies in the range 0.5 mm to 0.9 mm, depending on the chosen quench parameters.

By using gas quenching, the hardness attains values of up to 690 HV0.5 (Fig. 4b). It can be established for an air pressure of 0.6 MPa that the transition from the hardened zone to the heat treated core appears less clearly than that for an

![Fig. 2. Initial heat treated microstructure in the region of the tooth flank.](image)

![Fig. 3. Hardness profiles in the region of the tooth flank from induction hardened gears wheels using a polymer solution quench.](image)
air pressure of 0.3 MPa. The hardening depths obtained for air pressures of 0.6 MPa and 0.3 MPa have values of 1 mm and 0.73 mm, respectively.

Analysis of the edge zone shows a tempered martensitic microstructure (Fig. 5). With increasing depth and after crossing the transition zone, this structure merges into the heat treated microstructure of the tooth’s core. The tooth’s core and the induction hardened edge zone can be clearly observed in Fig. 5 by means of their different brightness. Using light-microscopy, no differences in the microstructures can be discerned between the polymer solution, water–air spray and gas quenched gearwheels. It can be seen from Fig. 5a that the tempered martensitic zone in the region of the tooth crest is larger that that in the tooth

Fig. 4. Hardness profiles in the region of the tooth flank of induction hardened gearwheels using: (a) spray cooling; (b) gas quenching.

Fig. 5. Microstructure of an induction heated and water–air spray quenched gearwheel: (a) Overview image of a tooth; (b) Tempered martensitic microstructure in the edge region.
flank's region. This corresponds with the hardening depths' range between 1.6 mm and 3 mm which was measured for the spray cooling.

3.2. Residual stresses

Prior to induction hardening using spray cooling, the heat treated gearwheel's residual stress state was investigated in the region of the tooth flank. It can be seen from Fig. 6 that, following heat treatment; i.e. in their initial state (designated as OC in the diagram), the tooth flanks exhibit compressive residual stresses of approximately 70 MPa. It is noticeable that a difference in the residual stress magnitudes exists between the left and right sides of the tooth's flanks. Induction hardening by means of a polymer solution leads to an elevation of the compressive residual stresses. The maximum values were obtained with a quench delay and then quenching at a pressure of 0.2 MPa. A comparison of the two flanks shows a difference of 20 MPa. This turns out to be low in contrast to quenching at pressures of 0.2 MPa and 0.3 MPa without a quench delay. Quenching at a pressure of 0.2 MPa leads to compressive residual stresses at a level of 290 MPa or 240 MPa. Quenching at a pressure of 0.3 MPa shows a difference in the compressive residual stresses of 150 MPa between the flanks. Thus a higher pressure leads to a larger difference in the residual stress values between the tooth's flanks.

The compressive residual stresses are depicted in Fig. 7 for increasing water pressure at a constant air pressure of 0.3 MPa. It is noticeable that the maximum magnitudes of compressive residual stress vary between 260 MPa and 275 MPa for water pressures of 0.1 MPa to 0.4 MPa. Not until a water pressure of 0.5 MPa, is the maximum magnitude of hardness reduced to 180 MPa. The maximum compressive residual stress of 275 MPa was obtained using a parameter set 0.3A-0.4W. The difference between the compressive residual stresses in the two flanks of a single tooth, observed for polymer quenching, also appears during spray cooling. The difference in the compressive residual stresses increases with rising water pressure, particularly on elevating the water pressure from 0.3 MPa to 0.4 MPa or 0.5 MPa. The smallest difference of 40 MPa in the compressive residual stresses was obtained for a water pressure of 0.1 MPa.

The compressive residual stresses, as a function of the water pressure at constant air pressures of 0.4 MPa and 0.5 MPa, can be seen in Fig. 8. It is evident that, in comparison to the air pressure of 0.3 MPa, the highest magnitudes of compressive residual stresses range over a lower level. The highest magnitude of 220 MPa for the air pressure of 0.4 MPa was obtained using a water pressure of 0.3 MPa. A maximum compressive residual stress of 260 MPa was realised by using the parameters 0.5A-0.4W. In comparison to the air pressures 0.3 MPa and 0.4 MPa, it is noticeable that the difference in the compressive residual stresses between two tooth flanks is largest for the air pressure of 0.5 MPa. The parameter set 0.5A-0.3W leads to a tensile stress of 10 MPa in one of the tooth's flanks. This set and the parameter set 0.5A-0.4W lead to a maximum difference of 245 MPa in the compressive residual stresses.

The gearwheels induction hardened using gas quenching exhibited compressive residual stresses in their tooth flanks which lay in the range between 300 MPa and 345 MPa and thus approximate the residual stress level obtained by using polymer quenching (compare Fig. 9 and Fig. 6). In compar-
ion to polymer quenching and quenching using water—air spray cooling, the variations in the residual stress magnitudes between two tooth flanks are smaller. Intensifying the gas quenching, i.e. elevating the air pressure to 0.6 MPa, leads to a larger difference in the residual stresses between the tooth’s flanks. The lowest residual stress difference of 15 MPa was obtained by using an air pressure of 0.3 MPa.

4. Discussion

The residual stresses, measured for both the water—air spray cooling as well as the gas cooling, are analogous to those specified by using polymer quenching. A common mechanism of residual stress formation underlies both quenching procedures.

During the induction heating, a temperature gradient arises between the surface layer and the core. The surface layer’s thermal expansion leads to the formation of compressive thermal stresses. On exceeding the yield strength, plastic deformation is induced in the surface layer which, for large temperature gradients, can continue into the core. During quenching, the surface layer contracts more strongly than the core owing to the higher cooling rate. As a consequence, tensile stresses arise in the surface layer. On reaching the yield strength of austenite, plastic deformation of the austenitised surface layer occurs. The development of the tensile stresses ceases on attaining the martensitic start temperature of the volumetric expansion existing in and caused by the transformation of the surface layer. The result is a build-up of compressive stresses. It must be pointed out that the biggest plastic elongation is achieved at the end of the tensile stress phase just before the surface layer starts to transform into martensite [12].

Whereas light-microscopy had identified no differences between the martensitic microstructures produced by using either polymer quenching, spray cooling or gas hardening, the hardness measurements yielded slight differences in the hardness values in the hardened zone of the tooth flanks for the 3 quenching procedures.

A comparison of the residual stress values for the spray cooling and the polymer quenching shows that the maximum compressive residual stresses obtained using polymer quenching are higher than those using the spray cooling. This could be attributed to the different wetting kinetics of these procedures and their resulting cooling characteristics. It is known that the polymer solution forms an insulating vapour film on the hot surface which, depending on the polymer’s concentration, dissolves at a temperature below approximately 75 °C. As a consequence of the insulating effect of the polymer film, the cooling rate is reduced [13]. The spray cooling is characterised by intensive quenching features. This is attributed to a high level of bubble formation in the incipient boiling phase compared to other quenching procedures and the small bubble size. Thus, the heat can be more effectively conducted away [14]. As a consequence, this leads to higher thermal stresses which have a tensile character. In this way, the tensile residual stress measured in one of the tooth’s flanks for the parameter set 0.5A-0.3W can be explained. In comparison to polymer quenching and quenching by using water—air spray cooling, gas cooling demonstrates a different heat transfer mechanism. This is distinguished by the absence of film formation and incipient boiling phases characteristic of polymer quenching and water—air spray cooling, respectively. The heat is transferred convectively and thus less effectively. The temperature gradients are significantly lower compared to the water—air spray cooling and polymer quenching [15]. The thermally induced tensile stresses are comparatively low.

It was possible to establish differences of final state at flank 1 and flank 2 of a tooth for all three quenching procedures investigated. This was observed more clearly at higher pressures. The smallest variation was obtained by using gas quenching. This observation could be explained by a shadowing effect on the flanks arising through the gearwheel’s rotation during the quenching phase. As a consequence of this, the surfaces of the tooth flanks are not uniformly wetted. It should be able to inhibit this effect by alternating the gearwheel’s rotation. Another explanation for this effect is the gearwheel’s origin state, since the initial residual stress state analysis showed differences at flank 1 and flank 2. Due to machining by milling and the following heat treatment before induction hardening an initial residual stress state is formed, which leads to inhomogeneous distribution of residual stresses. In [16] the influence of hardening on residual stresses and distortion of tubes made of the rolling bearing steel (100Cr6) was investigated. An inhomogeneous tangential stress distribution in the circumferential direction of the tubes was detected before hardening. The author came to the conclusion that the tube manufacturing process leads to an uneven tangential stress distribution.

5. Conclusions

The investigations carried out here show that by appropriately choosing the quenching parameters in terms of water and air pressures, polymer quenching can be substituted by water—air spray cooling in the process of induction hardening using simultaneous dual frequency technology. In summary, the following conclusions can be drawn:

1. By using water—air spray cooling, compressive residual stresses can be produced in the surface of induction heated gear toothed components during controlled quenching. The magnitude of the compressive residual stresses is influenced by the choice of the quenching parameters.

2. Quenching at high water pressures leads to elevated hardness values. An analogous tendency was not established for the compressive residual stresses. Higher air pressures at comparable water pressures do not lead to an increase in the compressive residual stresses.

3. A maximum compressive residual stress of 275 MPa for a minimum residual stress difference between the tooth’s flanks of 40 MPa was obtained using air and water pressures of 0.3 MPa and 0.1 MPa, respectively.

4. High water pressures lead to large variations in the residual stress values between the tooth’s flanks. Analogous to the water—air spray cooling, larger variations were caused by elevating the medium’s pressure during polymer and compressed air quenching.

5. Gas quenching leads to high compressive residual stresses with lower variability. The hardness values obtained using gas quenching are lower than those for the water—air spray cooling.

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It was experimentally demonstrated that it is possible to controllably specify the residual stresses by means of the water–air spray cooling. From an economic viewpoint, such an approach for small batches is only expedient to a limited extent. In this regard, forecasting the hardness results based on numerical simulations would be advantageous and should be an objective of future research.

Within the scope of this work the residual stresses were evaluated at the surface only. For the potential fatigue behaviour evaluation distribution of residual stresses are necessary. Appropriate investigations will be part of the future work.

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