DOI: 10.1002/srin.201000218 steel research int. 82 (2011) No. 4

Induction Hardening of Spur Gearwheels Made from 42CrMo4 Hardening and Tempering Steel by Employing Spray Cooling

Dmytro Rodman[1)]*, Christian Krause[2)], Florian Nürnberger[1)], Friedrich-Wilhelm Bach[1)], Klaus Haskamp[3)], Markus Kästner[3)], and Eduard Reithmeier[3)]

[1)] Faculty of Mechanical Engineering, Institute of Materials Science, Leibniz University Hanover, Germany
[2)] Eldec Schwenk Induction GmbH, Germany
[3)] Institute of Measurement and Automatic Control, Leibniz University Hanover, Germany
* Corresponding author; e-mail: d.rodman@iw.uni-hannover.de

As a rule, induction surface hardening is carried out industrially by employing polymer solutions since these ensure a more homogeneous quench than immersion cooling in water. Besides reproducing the quenching process, the intention here is to minimise the hardening defects and the distortions arising from the heat treatment. Polymer solutions also have a few disadvantages which include, among others, poor environmental compatibility and handleability. Quenching by means of spray cooling provides an effective alternative. The purpose of the current investigation is to substitute the polymer solution by a water-air spray in induction hardening equipment for surface hardening spur gearwheels made of 42CrMo4 hardening and tempering steel. The suitability of spray cooling was assessed by means of hardness measurements, residual stress conditions, distortion measurements and by metallographic examinations. Based on the analyses currently carried out, it was possible to show that the two-phase spray cooling represents an alternative quenching method which produces comparable component properties.

Keywords: Induction surface hardening, spray cooling, 42CrMo4

Submitted on 28 September 2010, accepted on 30 September 2010

Introduction

Induction hardening by means of the "Simultaneous-Dual-Frequency" technology (SDF®) is based on rapidly austenitising the component's region to be hardened using an inductor which possesses two oscillating circuits and one power supply. The medium and high frequencies (MF and HF) which are thereby simultaneously available enable the contours of components with complex geometries to be precisely hardened by means of the separated power settings [1]. Owing to the short heating durations, which lie within the range from 100 ms to 500 ms, and the concentration of heating at the surface region, the hardening process involves low energy costs. Moreover, the low distortion results in reduced costs for reworking [2, 3].

In practice, quenching during induction surface hardening is carried out by employing aqueous polymer solutions which, unlike water, reduce the temperature dependency of the quenching effect and thereby the thermal stresses which occur. By means of this, hardening cracks can be avoided and distortions can be minimised. A controlled quench via a polymer solution can be guaranteed if its concentration and deposition is adapted to the geometry and the material specifications of the component to be hardened. In practice, this is frequently not implemented and consequently hardening defects in the form of non-uniform hardness, soft spot formation and distortion results [4].

In contrast to this, spray cooling provides good controllability in which a water-air mixture is produced by employing two-component nozzles with which the quench rate can be controlled with respect to a targeted location and time. By combining the induction heating process with the water-air spray cooling, a cost-saving and environmentally-friendly hardening procedure having a high reproducibility is the subject of the following investigations. Using the example of a spur gearwheel made of 42CrMo4 hardening and tempering steel, a spray field which is adapted to the gearwheel geometry is integrated into the induction hardening equipment. The process is assessed by means of hardness, residual stress and distortion measurements as well as using the resulting microstructure. Gearwheels having the same geometry and quenched in a polymer solution are used as a reference.

Current State of Research

Quenching medium used for induction surface hardening. The choice of the quenching medium for induction surface hardening depends on factors such as the part's geometry, the material and its susceptibility to cracking as well as its hardenability and the medium's implementation and disposal costs. Moreover, handleability and environmental compatibility are important concerns. Regarding its handleability, water is the simplest and most cost-effective quenching medium. On hardening unalloyed and low alloy steels, this effervesces. Geometric parts which are characterised by low susceptibility to cracking can be quenched in water [5]. In contrast to the economies of employing water are the inhomogeneities during cooling due to the Leidenfrost effect and the crack formation caused by the high quenching effect on exceeding the Leidenfrost point [6]. One attempts to counter these disadvantages by using water based polymer solutions which, analogous to water, also effervesce and form a stable vapour film on the part's surface with decreasing temperature. The film's insulating effect reduces the cooling effect within the range of the martensite's formation temperatures and thereby reduces the associated thermal stresses. The quenching process can be specifically controlled by means of setting the polymer concentration which generally lies within the range of 5% to 15%. If, owing to economic factors in high-volume production, the required polymer concentration is rarely adjusted to the material and the part's geometry, then hardening defects can result. Their disposal costs and their skin-irritant properties count among the disadvantages of the polymer solutions. A more moderate quenching is also sought during the effervescence of mineral oil emulsions by means of extending the vapour-film phase. However, this occurs comparatively uncontrolled and leads to a quench effect comparable to that of water at lower temperature intervals which is characterised by high thermal stresses. For materials liable to distortion and cracking, quenching oils in immersion baths or for showering are employed [4, 5]. Using such additives as salt and soap the cooling characteristic of water can be changed. In [7] the influence of the salt and soap concentration in water on the heat transfer coefficient was investigated. The authors used an electrically heated metallic sheet which was cooled by water spray from one side. The temperature was measured on the opposite sheet side by an infrared camera. It was shown that higher soap and salt concentrations decrease the heat transfer coefficient and increase the Leidensfrost temperature. An alternative to quenching in liquids is provided by gases: For example, gas nozzle fields for high pressure quenching. For this, gases such as hydrogen, nitrogen, helium and argon are employed. Despite hydrogen's higher thermal conductivity in comparison to nitrogen, it is not used industrially due to the high risk of explosion. For economic reasons, helium is also not industrially employed. In contrast to this, nitrogen is suitable due to its chemical inertness and its low price. Notwithstanding this, gas quenching is associated with high consumption costs which can only be reduced to a limited extend by using a gas recycling plant since additional maintenance and repair costs are incurred. However, this cooling method is characterized by low distortion [8, 9, 10].

Taking into consideration the above mentioned disadvantages of conventional quenching methods, a spray cooling process using a mixture of water and air was developed which ensured good controllability of the quenching process by means of specifically setting the spray parameters. Besides the economies, the process is characterised by a high level of environmental acceptability. Spray cooling has been hitherto investigated as a technology for cooling e.g. Al-profiles subsequent to extrusion and casting. The focus of attention here was, for example, the dependency of the heat transfer on the hydromechanical spray parameters such as the droplet size and velocity [11]. Further investigations of the heat transfer during the spray cooling of extruded profiles having different thicknesses were carried out in [12, 13] in order to realise a controlled spray cooling by means of numerical simulations and to be able to determine the heat transfer coefficients and heat flux densities, respectively. Water-air spray cooling for surface tempering gear toothed components from the forging heat was successfully applied to gearwheels and pinion shafts in [14, 15]. In both papers, the authors conclude that the spray cooling technology, based on a specifically produced two-phase spray, enables a process-integrated heat treatment of precision forged gear toothed components to be carried out and therefore has a high potential for saving energy and costs.

Induction hardening using water spray cooling is presented in [16]. The authors used a system of ten nozzles to cool induction heated rings made of SAE 52100 bearing steel (100Cr6). The distortion was evaluated on the basis of out-of-roundness and the authors come to the conclusion that results are similar to oil quenching. An air cooling system was also investigated which resulted in low distortion. However this quenching method induced non-martensitic precipitations caused by insufficient cooling capacity for the chosen parts.

Using a cylindrical geometric model of Ck45 steel as an example, induction heating combined with quenching by means of water atomised by air is described in [17]. Here, the heating is provided using a variable frequency between 100 kHz and 500 kHz with a maximum output power of 25 kW. The authors establish that it is possible to specifically quench surface heated specimens.

Material and Procedures

Within the framework of this research, the spray cooling technology is integrated into induction heating equipment in the form of a computer controlled spraying field and thereby effect profile-precise surface hardening of spur gearwheels of 42CrMo4 hardening and tempering steel. Supplementing hardness and distortion measurements by means of metallographic and x-ray analysis methods, it is to be shown that the spray cooling represents an effective alternative to polymer quenching within the framework of the induction hardening process.

The induction heating equipment. 3 MW testing equipment made by the company eldec Schwenk Induction GmbH, which operates using a simultaneous dual frequency method, was employed for induction heating. The principle underlying this method consists of simultaneously transmitting two oscillating electromagnetic fields with different frequencies to a component's surface layer with the aid of an inductor. Here, two oscillating circuits, i.e. a high and a medium frequency, are used with one power supply. The high frequency range envisaged for hardening depths of 0.3 mm to 1 mm, which for example is concentrated on the tooth crest region, is 150 kHz to 350 kHz. The corresponding medium frequency, which for example deals with the tooth root region, ranges from 10 kHz to 25 kHz for a hardening depth of up to 2 mm. Since the power of both frequency ranges is separately controlled, the proportion of MF and the HF powers, which are each rated to 1.5 MW, can be individually varied according to the assigned task. In order to obtain profile-precise hardening without influencing the core, a very short heating duration is required which generally varies between 0.1 s and 1 s. Owing to the short soaking period, an accumulation of heat is attained such that the teeth can not be fully hardened. Thus in the case of profile-precise gear-tooth hardening, an increase in both the tooth flanks' wear resistance and as well as the tooth roots' fatigue strength under reversed stresses can be obtained whilst maintaining minimal geometric change due to distortion [1, 2, 18]. Following, the SDF®-process is referred to as induction hardening.

The spraying field. The designed spraying field consists of a control unit, pneumatic components to control the air and water pressures, internal-mixing two-component nozzles mounted on a holder for positioning and pressure vessels containing the water reservoir. The array can be quickly connected to the induction heating equipment and is suitable for spray cooling different gear-tooth geometries.

Six high pressure, two-component nozzles (type 1/8JJAU) made by the company "Spraying Systems" were used to produce the two-phase spray. These nozzles consist of a liquid nozzle (type 1/8JJPFJ2850) and an air nozzle (type 1/8JJPAJ73160). The nozzles are positioned using an annular nozzle holder (see **Fig. 1**) which can be expanded to 12 nozzles. Moreover, the nozzles' distance to the part's surface can be varied.

The construction of the nozzle holders allows for the parts to be centrally located. The spray cones meet at the middle of the annular nozzle holder. The nozzle holder is mounted in the induction heating equipment by means of stay tubes (see Fig. 1). This enables the set-up to be quickly installed or uninstalled in the induction heating equipment.

The control unit consists of an industrial PC using a Windows XP operating system with data processors made by the company "Advantech". The software "LabView 8.6" was employed as the user interface, with which the quench duration was set and the water / air pressures were adjusted within the range of 0.1 MPa to 0.5 MPa via the pneumatic components. Proportional pressure control and solenoid valves, manifold blocks and a pressure reducer count among the components for controlling the air supply pressure.

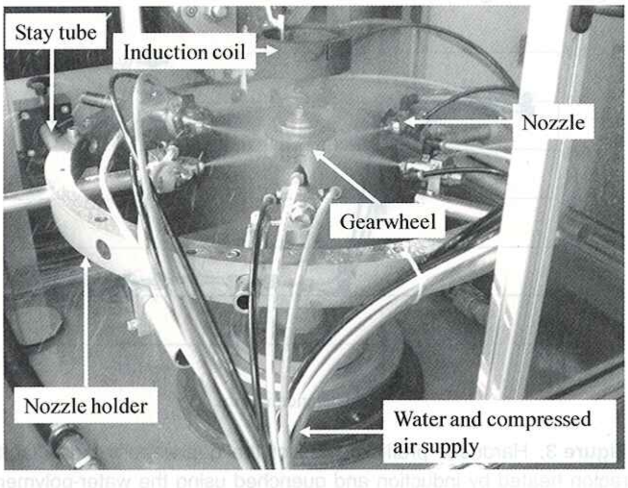

Figure 1. Spray cooling of an induction heated gearwheel.

Component under investigation. The investigated component involves a spur gearwheel made from 42CrMo4 (1.7225) hardening and tempering steel. The gearwheel possesses 28 teeth and has a module of 2.6. The corresponding pitch circle diameter is 72.8 mm. The gearwheel was manufactured by machine cutting. The gearwheel was subsequently pre-tempered. This heat treatment improves the fatigue properties of the core's microstructure. Furthermore, a homogeneous microstructure is produced with a fine and uniform distribution of carbon which favours the rapid austenitization during induction heating [19].

Induction hardening. Within the framework of the experimental testing, three quenching methods were employed. These involve quenching by means of a polymer solution, a water-air spray or cooling using compressed air. Here, quenching using a polymer solution was regarded as a reference since this is conventionally employed during induction surface hardening.

The gearwheel was induction heated by means of a HF-power of 420 kW and a MF-power of 405 kW within 0.21 s. During the heating phase, the gearwheel was rotated at a speed of 1000 rpm. Quenching was carried out immediately after the heating. During the quenching, the rotational speed of the gearwheel was reduced to 25 rpm to ensure uniform cooling of the austenitised surface layer. The quenching was performed for 15 s using an 8% polymer-water solution at a pressure of 0.2 MPa. Here, a conventional ring shower was employed without atomisation. Quenching by means of spray cooling was carried out using 0.3 MPa air and 0.3 MPa water pressures as the parameters. Here, the quench duration was 7 s. On using compressed air for quenching, an air pressure of 0.3 MPa was chosen in which the quench duration was 30 s.

Metallographic analysis and hardness measurements. To investigate the induction hardened microstructure and its hardness, the gearwheels were cut into segments, each with three teeth, using a wet cutting-wheel to avoid heating. These segments were mounted, ground and finally polished to a surface roughness of 1 μm. Subsequent to polishing, the surface layer's hardness profile was determined according to the Vickers hardness scale HV0.5 using a hardness testing machine "Duramin-20" made by the company "Struers". Here, the hardness profile and the hardness depth were each measured three times in the region of the tooth crest, the tooth root and the tooth's flank according to DIN EN 10328. The corresponding mean values were considered for the evaluation. For the metallographic analysis, the polished samples were etched in 2% nitric acid. The light-dark contrast produced by etching distinguished the core's microstructure from the hardened surface layer. The metallographic analysis of the etched samples was carried out using an Axioplan 2 reflecting-light microscope made by the company "Zeiss Jena".

Measurement of distortion. The geometric changes due to the heat treatment were detected by means of a fringe projection system made by the company GF Messtechnik, which is equipped with a digital micro mirror display, at the Institute of Measurement and Automatic Control, Leibniz University in Hanover. Here, a triangulation procedure is employed with which it is possible to areally determine geometrical dimensions. This type of device incorporates a fringe-projection sensor mounted on a vertical linear axis able to perform precise measurements. Using the measuring device, $2x10^6$ data points can be recorded in approx. 6 s. By means of a precision rotational axis in an air bearing, the gearwheel is positioned in the 45 mm x 35 mm x 18 mm measurement chamber and measured both prior to and after the heat treatment. By comparing both measurements, the distortion resulting from the heat treatment can be analysed. Here, the deviations in the pitch and radius are considered. Colour-coded differential images are produced to visualise and to assess the three-dimensional distortion [20].

Residual stress measurement. To measure the residual stresses which occur due to the heat treatment, in each case three teeth which are distributed around the gearwheel's circumference were removed by means of wire spark-erosion. The residual stresses were measured on the left and right hand tooth flanks using x-ray diffractometry according to the $\sin^2$ psi procedure [21] at the Institute of Production Engineering and Machine Tools, Leibniz University in Hanover. An x-ray diffractometer "XRD 3003 TT" was employed for this purpose. The measurements occurred on the α-iron lattice plane hkl (211) (156,084 °). The corresponding penetration depth was $\tau_{max} = 5.5\ \mu m$. The instrument possesses a 2 mm point collimator (CrKα-beam) with an accelerating voltage of 30 kV and a beam current of 35 mA.

Results

Hardness profile and microstructure. The hardness measurements in the tooth crest region of the gearwheel quenched using the water-polymer solution, the water-air spray and compressed air show that hardness profile for the water-air spray and the compressed air quenching is analogous to the water-polymer solution quenching (see **Fig. 2**). All three profile curves show a hardened surface layer. It is noticeable that in these curves, the hardness values obtained with water-air spray cooling lie somewhat below those of the water-polymer quenching.

The values in the hardened surface layer obtained using compressed air turn out to be lower than those for water-air spray cooling. At a hardness limit of 575 HV, the hardening depth in the tooth crest region is 3.06 mm, 2.57 mm and 2.72 mm for the water-polymer quenching, water-air spray cooling and the compressed air quenching, respectively, in which a hardness limit of 550 HV was assumed for the latter. Besides the hardened surface layer, two other regions can be identified. These involve a transition zone and the core's microstructure. Whilst the difference between the water-polymer quenching and the water-air and the compressed air quenchings is clearly expressed in the hardness values for the tooth crest region, this is not the case for the tooth flank region (see **Fig. 3**). It can be observed that the hardness values for the water-polymer quenching and the water-air spray cooling hardly differ from each other in the region of the hardened surface layer. The hardness values obtained by compressed air quenching lie somewhat below the values for water-air spray cooling. The hardening depths for water-polymer quenching, water-air spray cooling and compressed air quenching are 0.86 mm, 0.75 mm and 0.73 mm, respectively.

In the tooth root region, the hardening depths for the water-polymer quenching and the water-air spray cooling are 0.88 mm and 0.83 mm, respectively. The hardening depth obtained in the tooth root using compressed air is 0.81 mm. The hardness profiles (see **Fig. 4**) are analogous to those obtained for the tooth crest and tooth flank regions (cf. Fig. 2 and Fig. 3).

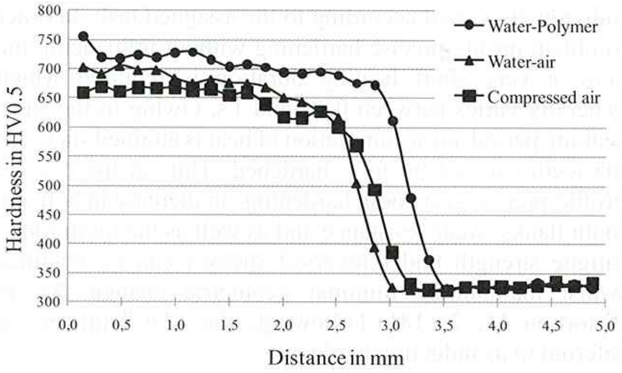

Figure 2. Hardness profile curves of the gearwheel's tooth crest region heated by induction and quenched using the water-polymer solution, water-air spray cooling and compressed air.

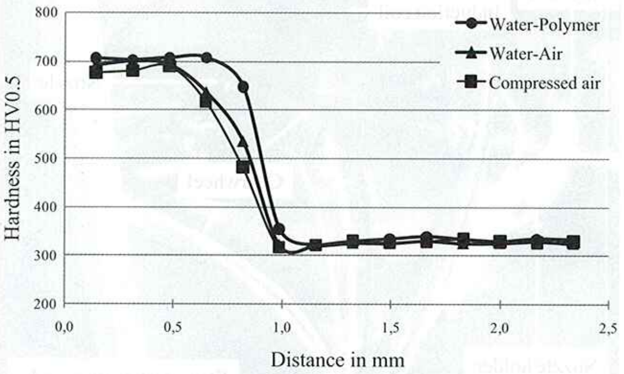

Figure 3. Hardness profile curves of the gearwheel's tooth flank region heated by induction and quenched using the water-polymer solution, water-air spray cooling and compressed air.

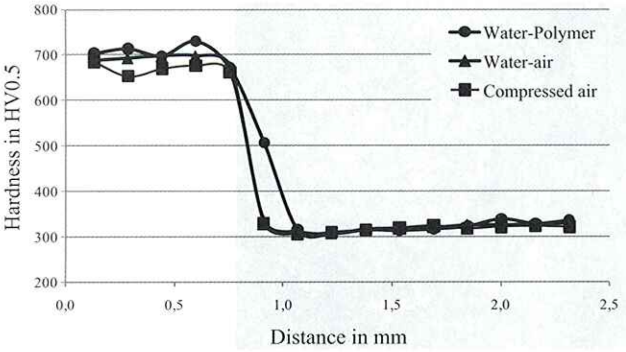

Figure 4. Hardness profile curves of the gearwheel's tooth root region heated by induction and quenched using the water-polymer solution, water-air spray cooling and compressed air.

To evaluate the scatter of the measured hardness values the standard deviation was calculated for every point in the diagrams above. For water-polymer quenching the standard deviation is within the range of 0.007 HV0.5 to 19 HV0.5. A few points showing standard deviation values more than 28 HV0.5 were qualified as outliers. Water-air spray quenching is characterized by an analogous standard deviation range. In comparison to water-polymer quenching it shows less outliers having values of about 25 HV0.5. The standard deviation range for compressed air cooling is from 1 HV0.5 to 17 HV0.5. Two points with values of 24 HV0.5 and 30 HV0.5 are out of this interval and can be considered as outliers.

The hardened regions identified in the hardness profile curves also arose during the metallographic examinations. In the macrographs, both the hardened surface layer as well as the core's microstructure is very conspicuous for all three quenching processes (see **Fig. 5**). The hardened surface layer consists of martensite with fractions of bainite. It can be established here that the martensitic microstructure is distinctively finer in the tooth crest than in the tooth root (see **Fig. 6**). This correlates with the higher hardness values in the tooth crest than those in the tooth root region (cf. Fig. 2 and Fig. 4). A comparison of the water-polymer quenching with the water-air spray cooling or with the compressed air quenching shows analogous microstructures in the tooth crest and tooth root regions. It can be established that the fraction of bainite obtained during compressed air quenching is higher in these tooth regions. This may indicate an insufficient cooling rate. The core consists of a tempered microstructure corresponding to the pre-tempered condition.

Residual stresses. The evaluation of the residual stress measurements show that the highest compressive residual stresses arise during the compressed air quenching (see **Fig. 7**). Here, compressive stresses of 313 MPa and 311 MPa were measured in the right and left tooth flanks, respectively. On comparing the water-polymer quenching with the water-air spray cooling, it is noticeable that the difference between the right and left tooth flanks' compressive residual stresses is larger for the latter. This is 21 MPa and 128 MPa for the water-polymer quenching and for the spray cooling, respectively. It is also noticeable that the compressive stresses measured on the right tooth flank are larger than those measured on the left for every quenching method. This is assumed to be attributed to the gearwheels' rotational motion during the quenching.

Dimensional and geometric changes. The distortion analysis based on the differential images show that the heat treatment due to the spray cooling produces a uniform distortion of the gear teeth (see **Fig. 8**). A distortion interval of ± 0.018 mm was measured for the three quenching methods. In the region of the tooth crest, it is noticeable that the distortions due to the water-polymer and the compressed air quenching fluctuate between positive and negative values (see **Fig. 8a,c**).

It can be discerned from the analysis of the pitch and radius deviations (see **Fig. 9**) that the deviation intervals obtained for all three quenching methods are similar in the tooth crest and tooth root regions. It is noticeable that the deviation intervals for the pitch is smaller for the case of the compressed air quenching than the corresponding intervals for the water-polymer and the water-air spray cooling. However, regarding the radius deviations, a larger deviation interval results for the compressed air quenching than for

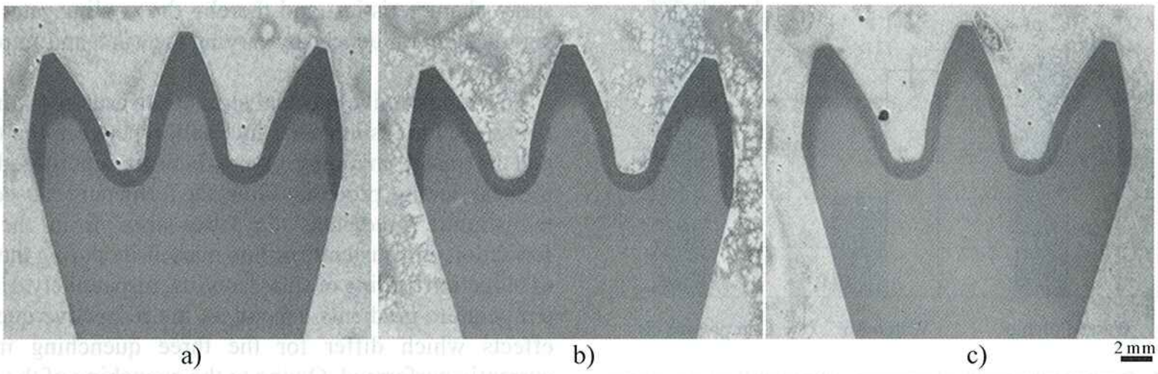

Figure 5. Macrographs of induction heated gearwheels subsequently quenched using a water-polymer solution (a), water-air spray (b) and compressed air (c).

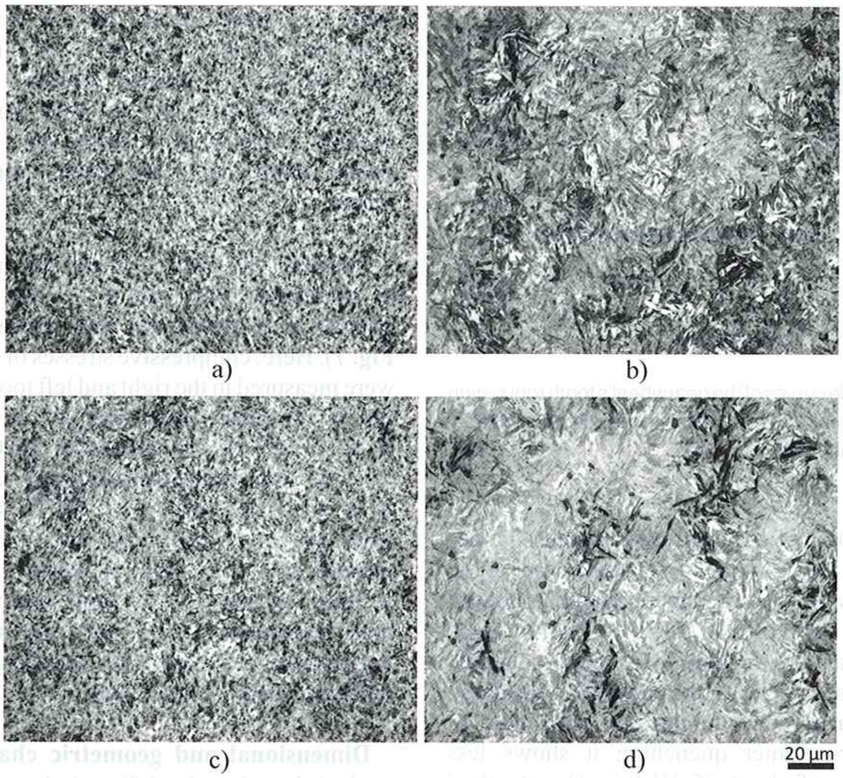

Figure 6. Martensitic microstructures of gearwheels quenched using a water-polymer solution in the tooth crest (a) and tooth root (b) and using a water-air spray in the tooth crest (c) and tooth root (d).

both of the other quenching methods. For the evaluation of measurement uncertainty of the fringe projection system a cylinder geometry was used. The measurement uncertainty was determined to ± 10 µm.

Discussion

The results show that quenching by means of water-air spray cooling represents an effective alternative to polymer quenching. Metallographic examinations demonstrate that by using spray cooling, a profile-precise martensitic surface layer can be produced which is analogous to that produced by polymer quenching. It is established that the hardness values obtained by means of water-air and compressed air quenching, using the current chosen process parameters, lie somewhat below those of the polymer quenching. This also applies to the corresponding surface layer hardness values. Owing to the identical austenitising conditions for all three quenching methods, this result can be attributed to the quenching conditions. The cause could be due to choosing a too low water deposition density. Within the framework of previous investigations [15], in which the same type of nozzles were employed, it was possible to establish that the spray characteristics, and thereby the cooling rate, can be significantly influenced by varying the water and air pressure ratios.

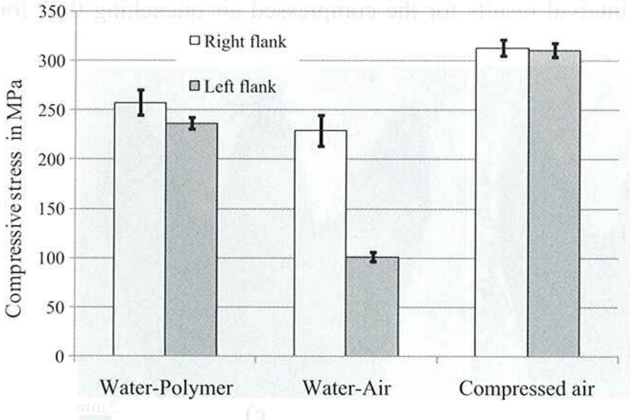

Figure 7. Compressive residual stresses at the tooth flanks' surfaces of gearwheels quenched using a water-polymer solution, water-air spray cooling and compressed air.

The compressive residual stresses measured on the tooth flanks are the result of the interaction between the thermal and the transformation stresses which are superposed during the heat treating process. Whilst the former are caused by the temperature gradients, the latter arise from the transformation into austenite or into martensite during the course of induction heating or spray cooling, respectively. Here, the temperature gradients depend on the respective quenching effects which differ for the three quenching methods currently performed. Owing to the quenching of the surface layer, which was previously heated to the austenitising temperature, it shrinks whilst simultaneously a volume

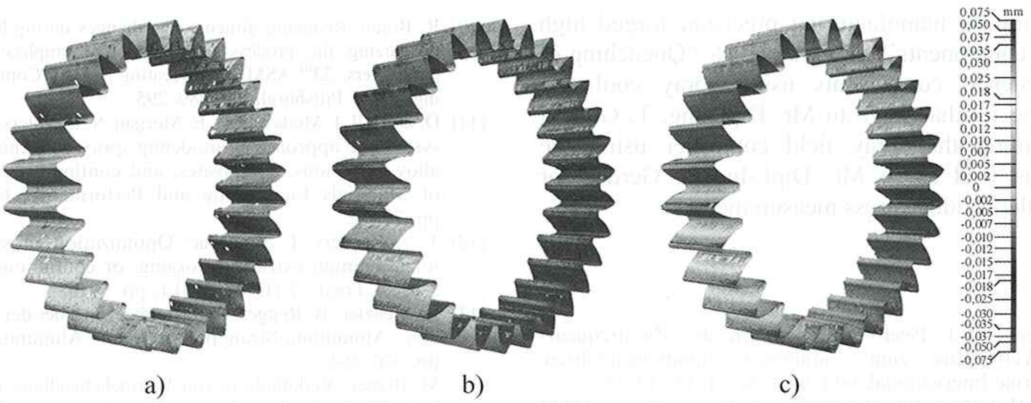

Figure 8. Differential images of gearwheels quenched using a water-polymer solution (a), water-air spray (b) and compressed air (c).

increase can arise due to the austenite-martensite transformation. The result of these processes is the measured compressive residual stresses which can be attributed to the different cooling profiles of the three quenching methods. Compressive stresses in the surface layer and tensile stresses in the core are characteristical for induction hardening. The former lead to a higher load capacity of components and prevent crack initiation [22]. However, compressive residual stresses have a significant influence on the dimensional and geometric changes. Here, the homogeneity of the cooling plays a crucial role. This depends on the quenching medium's wetting behaviour. For the three quenching methods, it was established that a comparable distortion resulted. The three quenching methods differ with regard to the distortion's distribution. In comparison to the polymer and the compressed air quenching, the distortion for the water-air spray cooling is uniformly distributed which suggests a homogeneous wetting behaviour of the spray cooling. The inhomogeneous distortion for the polymer quenching can, under certain conditions, be attributed to an unstable formation of the polymer film which initially breaks down at the edges and corners and can thus lead to non-uniform cooling.

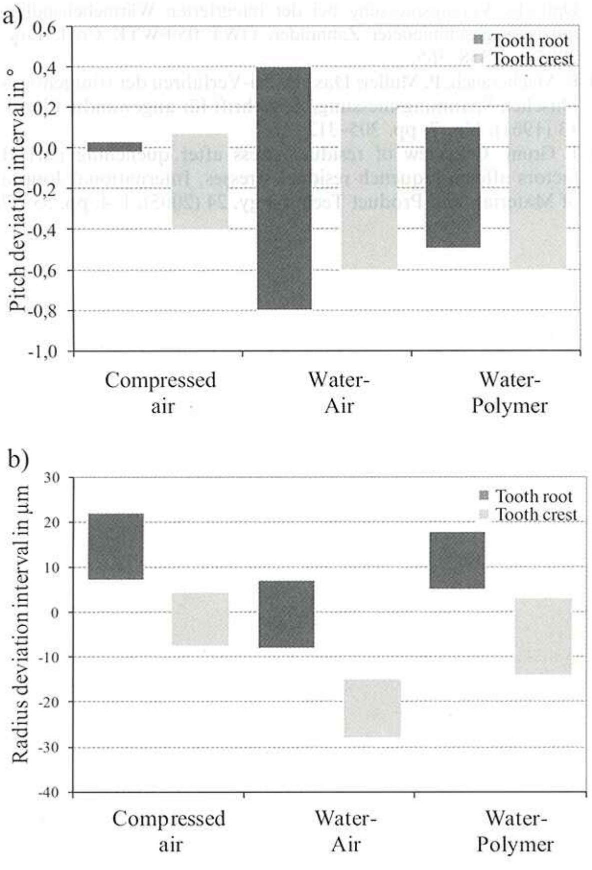

Figure 9. Pitch (a) and radius (b) deviations in the tooth crest and tooth root regions resulting from water-polymer, water-air and compressed air quenching.

Conclusions

The investigations carried out here demonstrate that spray cooling can be successfully used for induction surface hardening. Using spray cooling, microstructural and hardness gradients, comparable to polymer quenching, can be adjusted for low and uniform dimensional and geometric changes. Hardnesses and compressive residual stresses obtained with spray cooling differ somewhat from those produced by polymer quenching. Within the framework of future investigations, these differences are to be specifically adjusted by means of suitably choosing the spray parameters. Here, it is necessary to minimise the compressive residual stress difference between the left and right tooth flanks and to increase the stress magnitudes. Moreover, the influence of the spray parameters on the dimensional and geometric changes is to be investigated with the intention of reducing them.

Acknowledgements

The authors would like to thank the German Research Foundation for financing the current work within the framework of the Collaborative Research Centre 489

"Process chain for manufacturing precision forged high performance components", sub project T6 "Quenching of induction-hardened components using spray cooling". Above all, special thanks go to Mr. Dipl.-Ing. T. Gretzki for programming the spray field controller using the LabView® as well as to Mr. Dipl.-Ing L. Gerdes for carrying out the residual stress measurements.

References

[1] W. Schwenk, H.-J. Peter: Anwendungen des Zweifrequenz-Simultan-Verfahrens zum induktiven Randschichthärten, Elektrowärme International, 60 (2002), No. 1, pp. 13–18.

[2] H. Jehnert, H.-J. Peter: Einsatzhärten vs. Induktionshärten, HTM J. Heat Treatm. Mat, 64 (2009), No. 2, pp. 72–78.

[3] K. T. Jones, M. R. Newsome, M. D. Carter: Gas carburizing vs. contour induction hardening in bevel gears <http://gearsolutions.com/article/detail/5960/title/gas-carburizing-vs-contour-induction-hardening-in-bevel-gears> [State: March 2010. Access: 02.03.2010, 10: 35 CET].

[4] E. H. Burgdorf: Abschreckfehler beim induktiven Randschichthärten, HTM – Härterei-Technische Mitteilungen, 44 (1989), No. 3, pp. 179–182.

[5] H. Beitz: Kriterien für die Auswahl des Abschreckmittels für das induktive Randschichthärten, HTM – Härterei-Technische Mitteilungen, 44 (1989), No. 3, pp. 188–191.

[6] A. Karl: Untersuchung der Wechselwirkung von Tropfen mit Wänden oberhalb der Leidenfrost Temperatur, Shaker Verlag, Aachen, 1997.

[7] J. Krol, E. Specht: Influence of Quality of Water and Surface Roughness on Quenching Rate, International Conference on Continuous Casting of Non-Ferrous Metals, Proceedings, 2005 Neu-Ulm, pp. 118–123.

[8] J. Ohland, F. Hoffmann, H. W. Zoch: Gasabschrecken mit Luft, HTM – Härterei-Technische Mitteilungen, 61 (2006), No. 4, pp. 207–217.

[9] K. Löser, V. Heuer: Neue Entwicklungen auf dem Gebiet der Hochdruck-Gasabschreckung, HTM – Härterei-Technische Mitteilungen, 58 (2003), No. 2, pp. 74–82.

[10] R. Braun: Reducing dimensional changes during heat treatment by optimizing the process with particular emphasis on quenching parameters, 23rd ASM Heat Treating Society Conference, Proceedings, 2005 Pittsburgh, pp. 289–295.

[11] D. D. Hall, I. Mudawar, R. E. Morgan, S. L. Ehlers: Validation of a systematic approach to modeling spray quenching of aluminum alloy extrusions, composites, and continuous castings, Journal of Materials Engineering and Performance, 6 (1997), No. 1 pp. 77–92.

[12] T. A. Deiters, I. Mudawar: Optimization of spray quenching for aluminum extrusion, forging, or continuous casting, HTM J. Heat Treat., 7 (1989), No. 1, pp. 9–18.

[13] D. Menzler, B. Repgen: Wärmeübergang bei der Wasserkühlung von Aluminium-Strangpreßprofilen, Aluminium, 70 (1994), pp. 360–364.

[14] M. Breuer: Verknüpfung von Wärmebehandlung und Formgebung beim Präzisionsschmieden von Verzahnungen, Leibniz Universität, Hannover, 2000.

[15] C. Krause: Randschichtvergüten verzahnter Bauteile mittels einer Wasser-Luft-Spraykühlung, Leibniz Universität, Hannover, 2008.

[16] S. Segerberg, P. E. Naslund: In-line Hardening with Magnetic-Field Heating, 20th ASM Heat Treating Society Conference, Proceedings, 2000 St. Louis, pp. 316–320.

[17] F. Moreaux, P. Archambault, G. Beck, Y. Pourprix: Induktives Randschichthärten von Stahl Ck45 durch Abschrecken in zerstäubtem Wasser, HTM – Härterei-Technische Mitteilungen, 44 (1989), 3, pp. 129–132.

[18] W. Schwenk: Ersatz des Einsatzhärtens von Verzahnungsteilen durch induktives Randschichthärten, Elektrowärme International, 63 (2005), No. 4, pp. 173–175.

[19] V. Läpple: Wärmebehandlung des Stahls, 9, Verlag Europa-Lehrmittel, Haan-Gruiten, 2006, p. 186.

[20] M. Kästner, J. Seewig, E. Reithmeier, C. Krause, Fr.-W. Bach: Optische Verzugsmessung bei der integrierten Wärmebehandlung präzisionsgeschmiedeter Zahnräder, OWT 05+WTK Conf. Proc., 2005, pp. 358–365.

[21] E. Macherauch, P. Müller: Das sin^{2}Psi-Verfahren der röntgenographischen Spannungsmessung, Zeitschrift für angewandte Physik, 13 (1961), No. 7, pp. 305–312.

[22] J. Grum: Overview of residual stress after quenching part II: factors affecting quench residual stresses, International Journal of Materials and Product Technology, 24 (2005), 1–4, pp. 53–97.