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Gas quenching process optimization to minimize distortion of a thin-wall ring gear by simulation*

Optimierung der Gasabschreckung dünnwandiger Ringe für minimalen Verzug durch Simulation

Abstract/Kurzfassung

Of the differences between gas quenching and immersion quenching processes, the major difference is the presence of boiling during the early stages of quenching in oil or water. The formation of a vapor phase has a dramatic effect on both the overall and local rates of heat removal from the parts being quenched, and on part distortion. With the absence of a quenchant phase change, gas quenching is touted to result in uniform heat extraction, thus lessening part distortion. Gas quenching is not without inherent problems. Nonuniform gas flow around a part contributes to distortion, and nonuniform cooling at different locations contributes to the variance of distortion. This paper discusses difficulties associated with gas quenching a thin walled ring gear that is prone to distortion. Heat treat process simulation was used to model the low pressure carburization and high pressure gas quenching of a carburized 5130 steel ring gear. Process variables investigated include fan speed and cooling durations of different quenching stages. The intent is to reduce distortion by controlling the overall gas velocity through adjustment of the fan speed, whereby the local cooling rates can be controlled to better accommodate the dimensional change associated with steel phase transformations during quenching. ■

Keywords: Low pressure carburizing, gas quenching, distortion, phase transformation, finite element modelling, optimization, heat treatment simulation

Der bedeutendste Unterschied zwischen der Abschreckung mit Gas oder durch Eintauchen in Flüssigkeit ist das Sieden beim Abschrecken in Öl oder Wasser. Die Ausbildung einer Dampfphase beeinflusst sowohl den gesamten als auch den lokalen Wärmeübergang an der Bauteiloberfläche – und damit auch den Bauteilverzug – dramatisch. Gasabschreckung hingegen beinhaltet keine Phasenumwandlung des Abschreckmediums und wird deswegen als homogener hinsichtlich Wärmeübergang und Verzug angesehen. Allerdings ist auch die Gasabschreckung nicht unproblematisch. Ungleichmäßigkeiten im Gasfluss um das Bauteil herum tragen zum Verzug genauso bei wie ungleichmäßige Abkühlung zu dessen Varianz. Diese Studie behandelt die Schwierigkeiten bei der Gasabschreckung von dünnwandigen Ringen, die stark zu Verzug neigen. Zu diesem Zweck wurde der Wärmebehandlungsprozess mit Niederdruckaufkohlen und anschließender Hochdruck-Gasabschreckung eines Rings aus dem Stahl 5130 simuliert. Untersucht wurden Einflüsse der Prozessvariablen Gasflussgeschwindigkeit und Abkühlungsdauer bei verschiedenen Temperaturstufen. Das Ziel ist eine Verzugsreduktion durch geregelte Gasflussgeschwindigkeit über eine Steuerung der Gebläsedrehzahl, wobei die lokale Abkühlungsgeschwindigkeit angepasst wird, um die Dimensionsänderungen aufgrund der Phasenumwandlung des Stahls beim Abschrecken zu kompensieren. ■

Schlüsselwörter: Niederdruck-Carburieren, Gasabschrecken, Verzug, Phasenumwandlung, Finite-Elemente-Modell, Optimierung, Wärmebehandlungssimulation

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1 Introduction

During quench hardening process of steel components, distortion is inevitable due to stresses generated by phase transformations and thermal gradients. It is required to have effective phase transformation and multi-phase mechanical models to predict quenching hardening results, including volume fractions of phases, hardness, residual stresses and distortion. More advanced computer simulation technology and tools has been developed in recent years, and it has been successfully used to solve industrial problems [1-5].

Vacuum carburization followed by gas quenching has become more widely used by the steel heat treat industry over the past decade. Compared to the traditional gas carburization process, vacuum carburization reduces furnace time, and provides bet-

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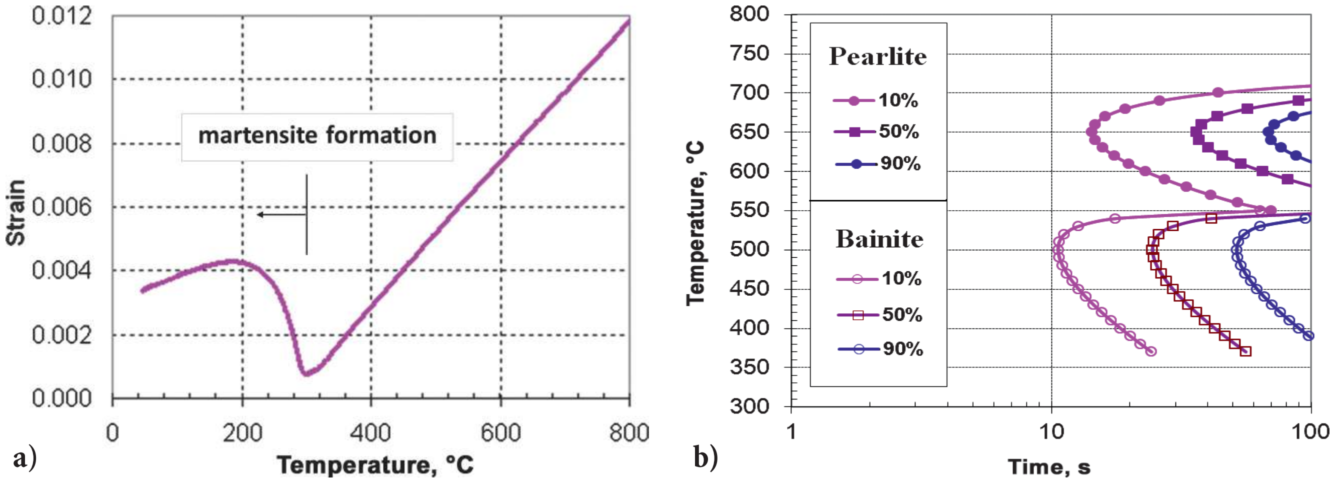


Fig. 1. Phase transformation kinetics: a) continuous cooling dilatometry experiment for AISI 5140 sample, b) TTT diagram for 5130 steel generated from DANTE database

Bild 1. Phasenumwandlungskinetik: a) Dilatometerkurve einer kontinuierlichen Abkühlung einer AISI 5140-Probe, b) ZTU-Diagramm Stahl 5130 aus DANTE-Datenbank

ter control of the carbon profile in the case, in general [6-8]. Two main gases used as carbon sources in vacuum carburization are acetylene and propane. The tremendous effect of carbon in iron on hardness and strength, and also hardenability is well known, as the carbon content strengthens iron and changes the kinetics of austenite decomposition. For example, higher carbon content increases the incubation time for the start of bainite formation, while also decreasing the bainite formation rate during the cooling and isothermal holding processes. Higher carbon content also depresses the martensitic phase transformation starting temperature. The effect of carbon content on phase transformations directly affects the internal stress condition during a quenching process. The vacuum carburization process provides more flexibility for control of the carbon profile in the case, so it is more possible to optimize the vacuum carburization boost/diffuse schedule to improve the residual stress state in the carburized and quench hardened parts.

Most commercial gas quenching production uses high pressure nitrogen as the quenching medium. Compared to traditional oil quenching, the gas quenching is environmentally friendly, and produces parts with clean surfaces, so washing after quenching is not required. Claims that gas quenching provides more uniform cooling and less distortion than liquid quenching are well accepted. However, care has to be given to the quenching furnace design, quenching process parameters, rack design, orientation of the parts, and the alloy hardenability. Quenching furnaces without reasonable gas flow uniformity can produce more distortion than liquid quenching. Quenching furnaces without enough cooling power to meet the commercial load demands can produce significant variance of distortion among parts at different locations in the rack [9, 10].

Due to the combination of inherent thermal gradients and the material volume change associated with steel phase transformations, the quench hardening is a high material nonlinear process. Optimization technology has been well developed and initially used in structural designs. In recent decade, the optimization technology has been widely used in all industries including heat treatment. With the heat treatment process modelling and optimization technology, the distortion can be reduced by optimizing the quenching process, such as by adjusting cooling rate [11]. In this paper, vacuum carburization and gas quenching of a thin walled ring gear are modelled using DANTE, a commercial finite element based software. The effects of gas flow pattern and cooling rate on distortion are investigated using a combination of modelling analysis and experimentally measured temperature histories at selected locations in the parts themselves and within the racked parts.

2 Phase transformation kinetics

The ring gear is made of AISI 5130 steel with a chemical composition of 0.83 % Mn, 0.22 % Si, 0.15 % Ni, 0.80 % Cr, 0.04 % Mo, and 0.30 % C (% indicates percentage by weight). The gear is carburized, so it is necessary to characterize the phase transformation kinetics over the range of carbon levels in the part in order to model the heat treatment process. Dilatometry experiments have been conducted for the base carbon level and several intermediate levels up to 0.8 % carbon previously for this steel grade [12]. Figure 1a shows a dilatometry curve for a continuous cooling experiment from 840 °C for an AISI 5140 steel sample. The phase transformation kinetics parameters for both martensitic and diffusive phase transformations were determined from such dilatometry data and have been stored in the software database of commonly used steels. Isothermal and continuous cooling phase transformation diagrams, i. e. TTT and CCT curves, can be generated from the database, as shown by the TTT curve in Figure 1b for AISI 5130. These diagrams can be generated to assist in planning the heat treatment schedule for a given alloy and part geometry.

3 Ring gear geometry and finite element model

A solid model of the ring gear used in this study is shown in Figure 2a. The outer diameter (OD) of the gear is 165 mm, the inner (tip) diameter (ID) is 141 mm, and the height is 20 mm. There are a total number of 97 inner teeth, as shown. This gear has a relatively thin wall and is prone to distortion. During the gas quench-

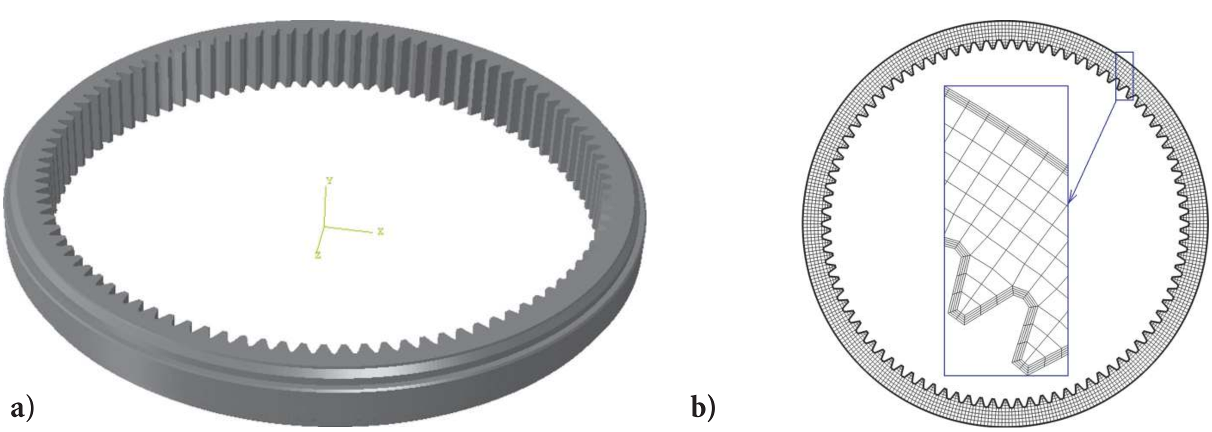


Fig. 2. a) Ring gear CAD model, and b) plane strain Finite Element Model

Bild 2. a) CAD-Modell eines Lagerrings, b) FE-Modell (ebener Dehnungszustand)

ing process, the thermal conduction through the thin wall (radial direction) is the dominant heat flow direction. For this gear, the main distortion mode is out-of-round distortion. To effectively and efficiently predict the out-of-round distortion, a two-dimensional plane strain model was developed, as shown in Figure 2b.

The gear is vacuum carburized, and then quenched using high pressure nitrogen gas. The finite element model contains 8010 nodes and 7380 quadrilateral elements. Fine surface elements are used to improve the calculation accuracy where there are steep thermal, stress and carbon gradients.

4 Vacuum carburization

Vacuum carburization, also known as low pressure carburization, has become a popular process due to reduced furnace time, excellent control of the carburization process, high product quality, and low carbon footprint. The required case depth for this gear is 0.5 mm, with the case depth defined by the distance from the surface to a depth with carbon content of 0.4 wt.-%. The desired surface carbon is 0.85 wt.-%. For this gear, acetylene is used as carburizing gas. DANTE-VCARB is a finite element analysis tool used to design boost/diffuse schedules for vacuum carburization processes to meet the surface carbon and case depth requirements. The vacuum carburization schedule is shown in Figure 3. The total boost time is 770 s and total furnace time is 3750 s, with the carburization temperature being 950 °C.

The predicted carbon distribution after carburization is shown in Figure 4a. The carbon contents of the outer diameter surface, the gear root surface, and the gear tip surface have significant differences due to geometry, as shown in Figure 4b.

5 Modelling distortion during gas quenching

High pressure gas quenching of rack loaded ring gears produced out-of-round distortion due to non-uniform cooling around the circumference of the gear. The cooling histories of several gears at different locations in the rack were measured. The particular gear discussed in this paper was instrumented with six thermocouples (TC) located in the gear at mid-height position, spaced every 60 degrees around the circumference. The TCs were brazed into radial holes, with the tips located near the outer surface. To model the cooling process, the surface of the gear was divided into 6 equal surface sections, as shown in Figure 5a, with TCs in the middle circumference of each section. Uniform thermal boundary conditions were applied in each section, including both the OD and ID surfaces.

The ring diameter was calculated using six pairs of nodal points as shown in Figure 5b; differences in these diameters were used to determine the out-of-round distortion. The intent was to document distortion caused by shape change, not size change, because the size change is consistent in general, and can be compensated by adjusting the green geometry during gear design. After gas quenching, the diameters at each pair of opposite nodes were calculated, and the out-of-round distortion was defined as the difference between maximum and minimum distances. The unit of distortion is millimeter.

The gears were carburized in a carburization chamber, and then transferred to the quenching chamber within 50 s. The temperature dropped about 50 °C during this transfer period. Predicted cooling curves for three locations are shown in Figure 6a. The model results were within 30 °C of the actual three TC locations when quenching this gear with 20 bar nitrogen at fan speeds of 40 % and 100 % of full speed. The three locations were separated by 120 degrees of arc, and TC #1 and TC #5 had the slowest and fastest cooling rates among the six TC's. Heat transfer boundary conditions were determined, assuming the ring gear could be described

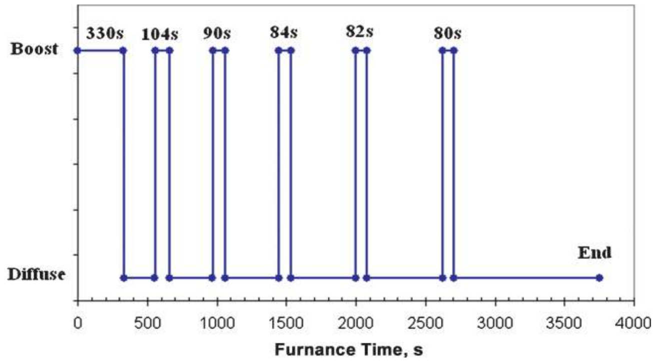


Fig. 3. Vacuum carburization schedule

Bild 3. Zeitabfolge beim Niederdruckcarburieren

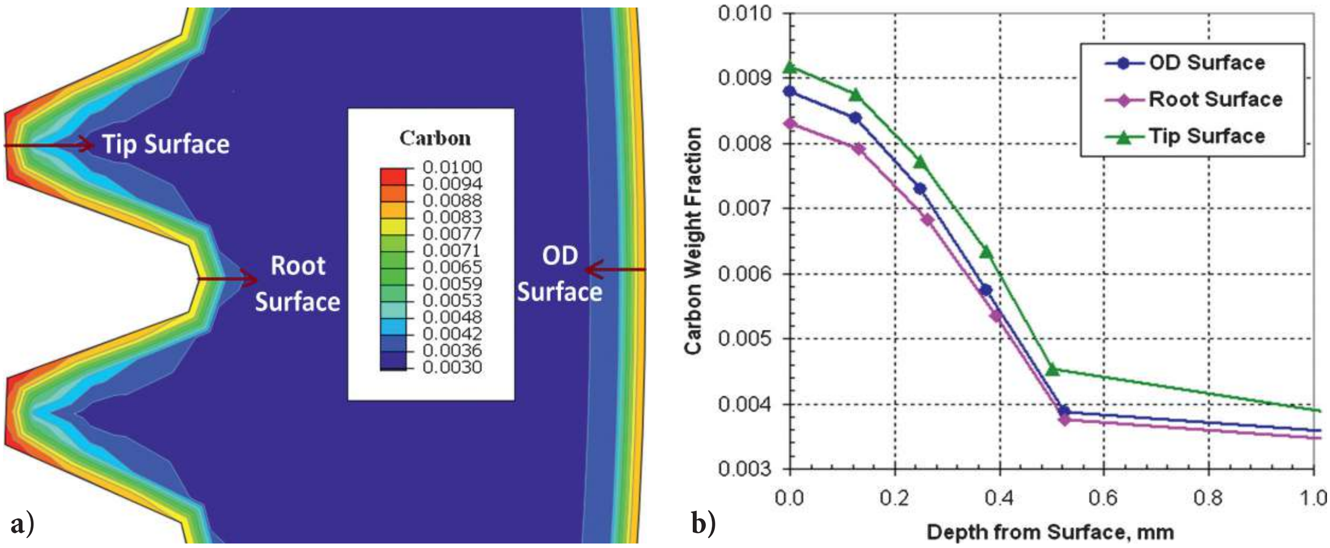


Fig. 4. Geometry effect on carbon distribution a) carbon distribution contour, b) carbon distribution curve plots

Bild 4. Einfluss der Bauteil-Geometrie auf die Kohlenstoffverteilung a) örtliche Kohlenstoffverteilung, b) Diagramm der zeitlichen Kohlenstoffverteilung

by six uniformly sized circumferential sections. In Figure 6a, the dashed curves are from predictions for the 40 % fan speed, and the solid curves are for 100 % fan speed. The measurements and predictions had a reasonable match, as mentioned. Further details about the gear position and racking arrangement with other gears cannot be presented due to proprietary issues, unfortunately.

The latent heat effect for this gear geometry and steel grade was significant, and it had to be accounted for in the computer models. In Figure 6b, the curve with solid data points is the predicted cooling history of TC #1 with the effect of latent heat included; this is for the 40 % fan speed. Also in Figure 6b is the result of a trial model that did not include the latent heat due to phase transformation, with all other conditions the same. This predicted cooling curve is shown by the curve with hollow data points, c. f. Figure 6b. The additional energy due to latent heat released by the phase transformation at TC #1 location is shown by the area between the two curves in Figure 6b. The predicted temperature difference caused by latent heat is more than 50 °C, which significantly contributes to the final distortion of the gear.

6 Gas quenching process optimization

As an approach for minimizing distortion, the gas quenching process was divided into 3 stages as shown schematically in Figure 7a. In this manner, the process can mimic an interrupted quench. Stage 1 and stage 3 are cooling stages with adjustable time and fan speed. The lower bound of fan speed is 40 %, and higher bound of fan speed is 100 %. The heat transfer boundary conditions for both 40 % and 100 % fan speeds were fit using the experimental data, and then applied in an optimization methodology to minimize the out-of-round distortion. The heat transfer coefficients and ambient temperature for fan speeds between these speed limits were calculated using linear interpolation. The second stage had a slow fan speed, and the purpose of this stage was to slow or stop heat loss and allow thermal conduction within the gear to reduce the temperature difference. There are a total of four design variables (DV) in this optimization model, and they are the fan speed of stage 1, cooling duration of stage 1, duration of stage 2, and fan speed of stage 3. The objective function is to rewduce the out-of-round dis-

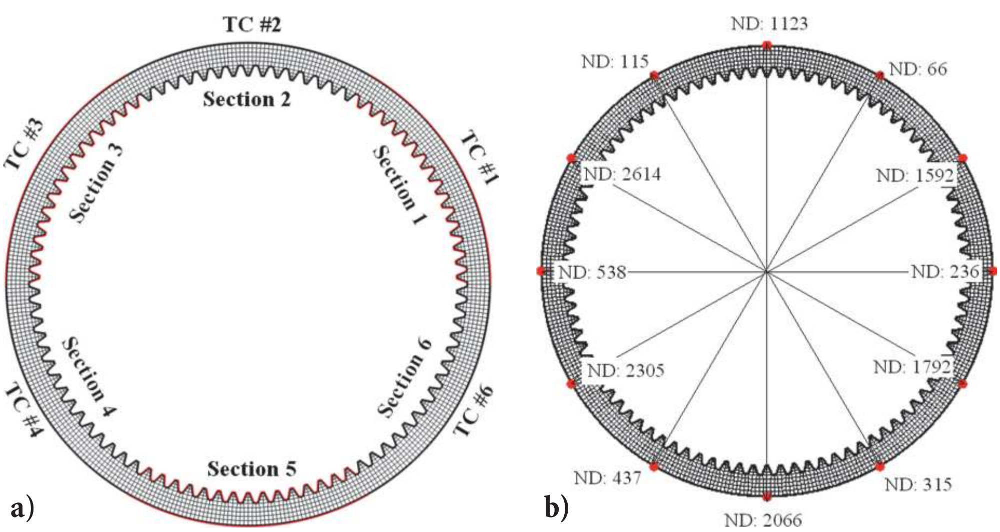


Fig. 5. a) Six surface sections and TC locations in the gear; b) definition of distortion from the deformed nodal positions

Bild 5. a) Sechs Oberflächenschnitte und Positionen der Thermoelemente im Lagerring, b) Definition des Verzugs anhand der Verschiebungen der Knoten

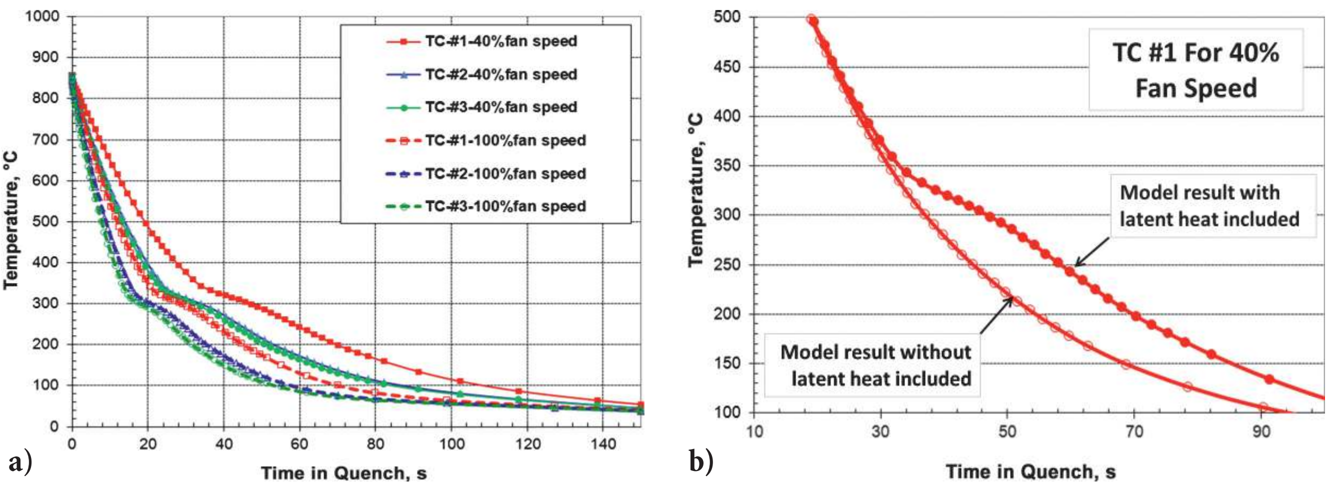


Fig. 6. a) Cooling curve comparisons between model results at indicated TC locations, and b) model results with and without latent heat

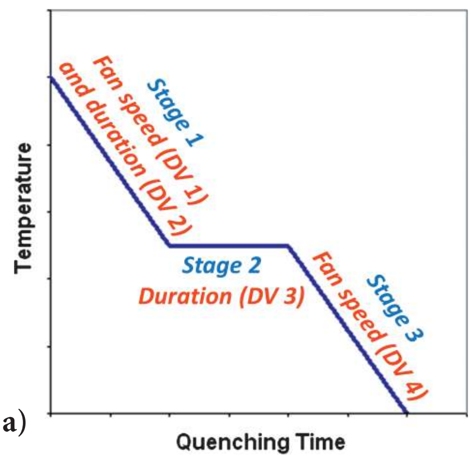
Bild 6. a) Vergleich der Abkühlkurven an den gezeigten TE-Positionen, und b) Simulationsergebnisse mit und ohne latente Wärme

tortion to below a specified allowable level. Constraints on the system included required surface and core hardness values. However, for this steel grade, the hardness requirement could be satisfied by even the slowest fan speed, so the constraints were not activated. Figure 7b shows the optimization strategy, where the four design variables were updated during each optimization iteration using sequential linear programming method [13]. The criterion of convergence used in this study was stabilized distortion values with five sequential iterations.

Figure 8 shows the results for the predicted effects of first stage and second stage hold times on final distortion. The graphs include results for both the 40 % and 100 % fan speeds in first stage cooling, and the differences are noticeable. Figure 8a shows that a small first stage hold time difference can result in large difference in final gear distortion. For example, for a 40 % fan speed in first stage cooling, a change in first stage cooling time from 22.3 s to 23.3 s is predicted to change the ring out-of-round distortion significantly from 0.12 mm to 0.28 mm. Similar wide variations in distortion are predicted as the first stage cooling time is increased. Large distortion differences due to a small process change indicate a process that is difficult, if not impossible, to control.

In Figure 8b, the effect of the stage 2 hold time is compared for two different first stage cooling routes. For both first stage conditions, second stage hold time is predicted to affect the final distortion in a difficult to control manner. While the graph shows that a second stage holding time duration for minimum distortion can be predicted, the ability to precisely control the abrupt changes in cooling conditions in practice as opposed to in the model is doubtful.

Figure 9a documents the reason for high sensitivity of distortion to the quenching process. The ring gear shape is shown at 22.3 s of first stage cooling and at 23.3 s of first stage cooling. Recall that Figure 8a showed that these particular first stage cooling times were predicted to produce widely different final distortions. What Figure 9a shows is that because of non-uniform cooling, the one second of additional cooling from 22.3 s (blue shape) to 23.3 s (red shape) produces 15 % martensite formation on one sector of the ring. This unbalanced martensite formation in the circumferential direction causes ring gear distortion to develop. Figure 9b shows the final distorted rings at the end of cooling per the models



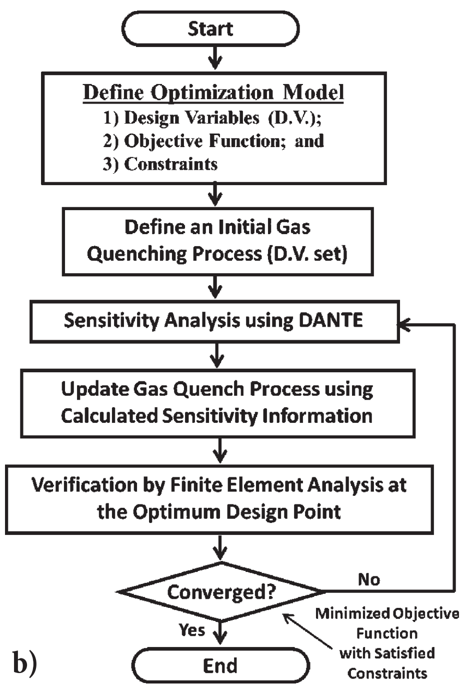


Fig. 7. a) Schematic plot of three cooling stages, and b) flow chart for gas quenching process optimization

Bild 7. a) Schematische Darstellung der drei Abkühlphasen, und b) Flussdiagramm für eine Optimierung der Gasabschreckung

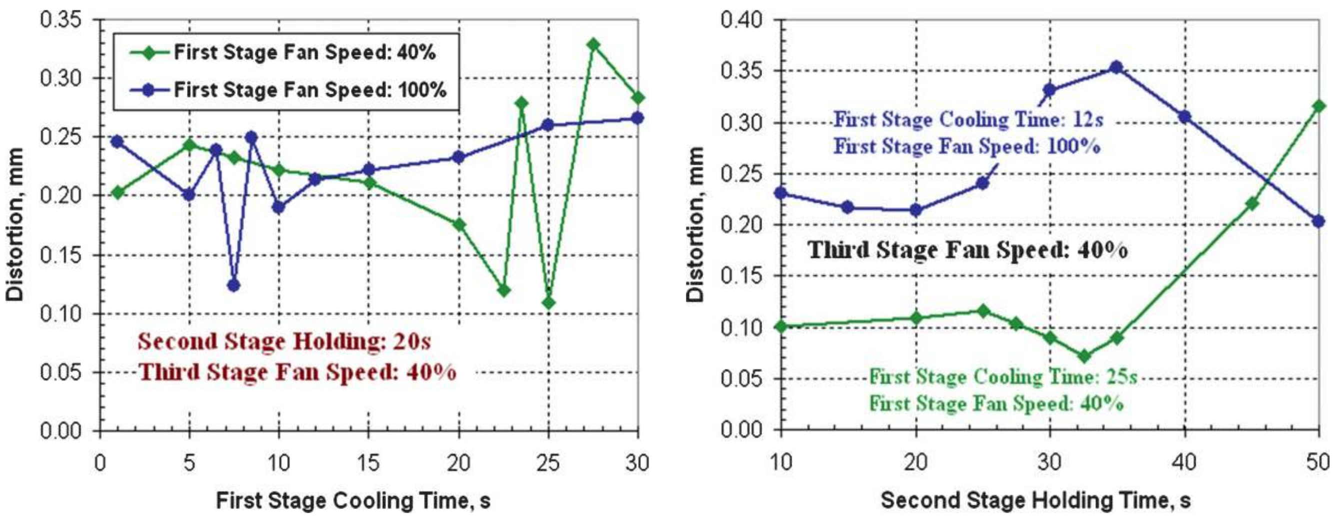


Fig. 8. a) Effect of first stage cooling time on final distortion, and b) effect of second stage holding time on final distortion

Bild 8. Effekt der Abkühlung in der a) ersten und b) zweiten Phase auf den resultierenden Verzug

reported in Figure 8a. The out-of-round due to nonuniform cooling and resultant nonuniform phase transformation is greater for a recipe with first stage cooling that is just 1 s longer than a recipe with a 22.5 s first stage cooling time.

7 Discussion

The experimental cooling curves for the three thermocouples clearly show the nonuniformity in cooling that was present for this particular nitrogen gas quenched ring gear. The modelling attempt was to optimize the cooling practice by adjusting the fan speed and hold time for three arbitrary stages of quenching so that distortion would be minimized. By controlling fan speed and cooling time, the models predict that distortion can be minimized in theory for this geometry and steel grade. However, practical considerations suggest that the sensitivity to timing is too great to achieve success strictly by controlling fan speed and application time. Other variables need to be examined to determine their effect on distortion, and how effectively they can be controlled. These other variables include gas pressure, alloy composition and the use of gas flow deflectors or vanes to improve the uniformity of cooling.

The uniformity of cooling is a big issue for gas quenching process. Merely eliminating a quenchant phase change does not guarantee uniformity of cooling. In gas quenching, the uniformity

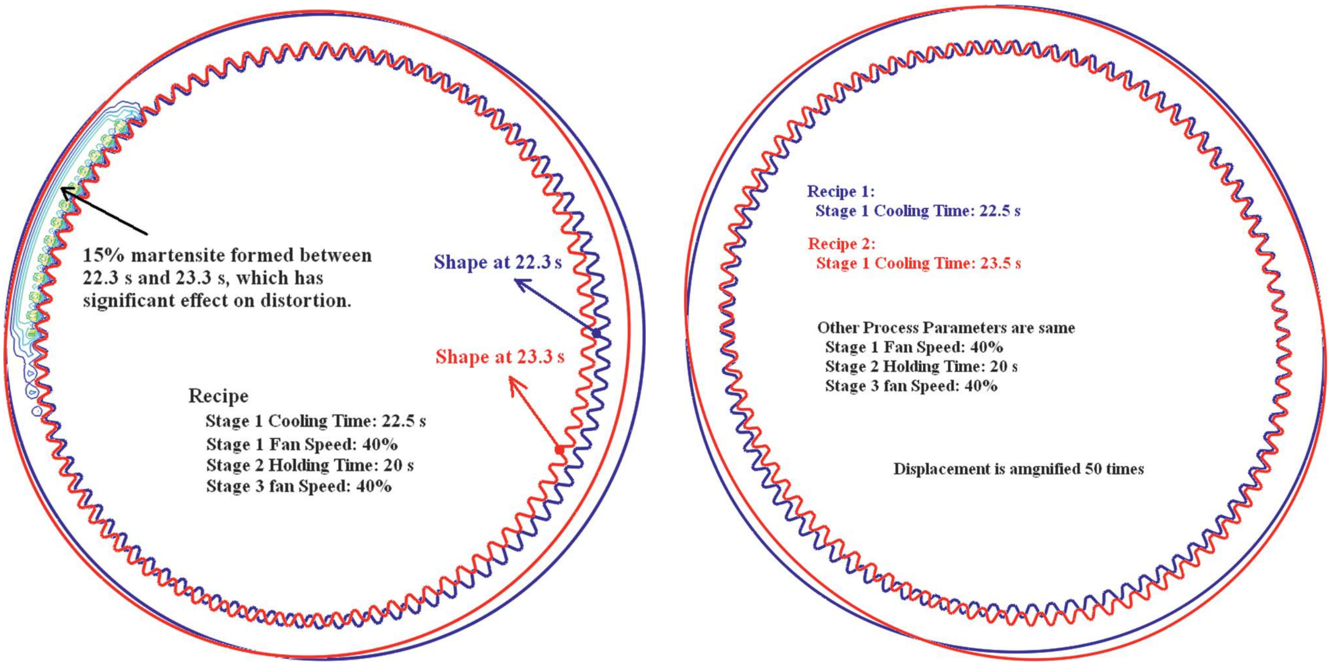


Fig. 9. Ring gear distortion: a) shape change for recipe 1 at 22.3 s and 23.3 s of cooling, b) out-of-round differences for a stage 1 cooling difference of 1 s

Bild 9. Verzug des Lagerrings: a) Formänderung bei Abkühlungsschema 1 nach 22,3 s und 23,3 s, b) Rundheitsabweichungen bei einer Abkühlungs-Differenz in der ersten Phase von 1 s of gas flow around each part in the rack is important. Also, the temperature pick-up by the gas as it circulates through the rack of parts is significant as this changes the cooling power of the gas. High pressure is good in part because the gas can extract more heat from the parts being quenched – there is more quenchant mass with increased gas pressure.

8 Summary

Heat treat process simulation was used to model the low pressure carburization and high pressure gas quenching of a carburized 5130 steel ring gear. The thin walled ring gear suffered significant out-of-roundness, and modelling was performed with the intention of determining process conditions that would lessen the out-of-round distortion. For this case, the optimization methodology sought to control cooling rate and temperature uniformity so that the phase transformation of austenite to martensite would occur uniformly within the part. However, the results showed that fan speed control and timing were not sufficient alone for achieving uniform cooling. While out-of-round could be improved, the process sensitivity was too great to achieve a practical recipe that would produce consistent results. Other variables must be included in the drive for greater uniformity of quenching.

Although not presented in this paper, the included thermocouple data and the additional thermocouple data directly show the non-uniformity in quenching this rack of ring gears. Computational fluid dynamics modelling of the quenching process would be a welcome step in better understanding gas quenching and in providing directions for process improvement.

References

1. *Ferguson, B. L.; Freborg, A. M.; Petrus, G.; Callabresi, M. L.:* Predicting the Heat Treat Response of a Carburized Helical Gear. Gear Technology *19* (2002) 6, pp. 20-25
2. *Inoue, T.; Arimoto, K.:* Development and Implementation of CAE System "HEARTS" for Heat Treatment Simulation Based on Metallo-Thermo-Mechanics. J. Mat. Eng. Perform. *6* (1997) 1, pp. 51-60
3. *Frerichs, F.; Lübben, Th.; Fritsching, U.; Lohner, H.; Rocha, A.; Löwisch, G.; Hoffmann, F.; Mayr, P.:* Simulation of gas quenching. J. Phys. IV France. 120 (2004), pp. 727-735
4. *Carlone, P.; Palazzo, G. S.:* Development and Validation of a Thermo-Mechanical Finite Element Model of the Steel Quenching Process Including Solid-Solid Phase Changes. Int. Appl. Mech. *46* (2011) 8, pp. 955-971
5. *Kang, S. H.; Im, Y. T.:* Thermo-Elasto-Plastic Finite Element Analysis of Quenching Process of Carbon Steels. J. Mat. Process. Techn. *192-193* (2007), pp. 381-390
6. *Hitoshi, I.:* Advanced Acetylene Vacuum Carburizing. IHI Engineering Review *38* (2005) 2, pp. 83-88
7. *Gorockiewicz, R.:* The Kinetics of Low-pressure Carburizing of Alloy Steels. Vacuum *86* (2011), pp. 448-451
8. *Kula, P.; Pietrasik, R.; Dybowski, K.:* Vacuum Carburization – Process Optimization. J. Mat. Process. Techn. *164-165* (2005), pp. 876-881
9. *Qin, M.:* Vacuum Carburization and High Pressure Gas Quenching Technology in Automotive Industry. Journal IHTSE *2* (2008) 3-4, pp. 116-120
10. *Heuer, V.; Löser, K; Leist, T.; Bolton, D.:* Enhancing Control of Distortion through 'One Piece Flow – Heat Treatment'. Fall Technical Meeting of American Gear Manufacturers Association, October 28-30, 2012, Dearborn, MI/USA, 2012
11. *Li, Z.; Grandhi, R.; Srinivasan, R.:* Distortion Minimization during Gas Quenching Process. J. Mat. Process. Techn. *172* (2006) 2, pp. 249-257
12. *Ferguson, B. L.; Dowling, W.:* Predictive Model and Methodology for Heat Treatment Distortion. NCMS Report, # 0383RE97, National Center for Manufacturing Sciences, Ann Arbor, MI/USA, 1997
13. Vanderplaats Research & Development, Inc.: DOT: Design Optimization Tools. Software, Version 5.0, 1999

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