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METALLURGICAL INFLUENCE ON QUENCH DISTORTION OF SAE 52100 LONG CYLINDERS[1]

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Abstract
Quenching of steel components results in complex and hard-to-predict dimensional and shape changes (distortion). Even the components manufactured from different parts of the same semi-finished product may show significantly different distortion behaviour during quenching. The reason is thought to be non-uniform distribution of distortion potential carriers in the final component (i.e., alloying elements, segregations, residual stresses and phases) which are accumulated throughout the whole manufacturing chain. This study focuses on the effects of alloying element distribution and segregation on quench distortion. For this aim, long cylinders of various diameters were machined from 45 mm diameter SAE 52100 steel bars, and marked to define their exact positions in the initial bar. Then, the cylinders were austenitized in a vertical furnace under nitrogen atmosphere and quenched in a gas nozzle field. The coordinate measurement results show that dimensional changes deviate significantly with machining position, however, the bending magnitudes and directions do not exhibit a distinct correlation with machining position and the cylinder diameter.
Keywords: Distortion; Gas nozzle field quenching; Shaft; SAE 52100.

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1 INTRODUCTION

Distortion is one of the most important problems during through-hardening of steel work pieces. It is a well known fact that distortion is a system attribute.[1] Certain distortion potential carriers (DPC) such as distribution of alloying elements, segregations, residual stresses and microstructure are brought into material during manufacturing,[1,2] which results in different distortion behavior even for samples from the same billet. Amongst these carriers, microstructure and alloying elements attract special interest since they may significantly affect transformation thermodynamics and kinetics. In certain cases, such as low carbon steels with Mn as an alloying element, the change of local carbon activity due to segregations may introduce development of insistent banded microstructures.[3]

During through-hardening process; isotropic dimensional changes due to volume change, and anisotropic dimensional changes and shape changes due to transformation plasticity and classical plasticity can be predicted by various physical models with the help of standard material data sets.[4] However, the quality of prediction is degraded due to the anisotropy which is brought in to material because of the inhomogeneous distributions of DPCs.[5,6] Therefore; a thorough understanding of their effect on distortion is of vital importance both for the justification of the results from current models and for the development of new models incorporating additional effects.

This study aims to reveal the effects of alloying element distribution and segregation structure on distortion of the cylindrical geometry. For this purpose, samples with varying diameters were cut from distinct positions in the cross section of a SAE 52100 billet, and then, through-hardened in a gas nozzle field in order to investigate dimensional and shape changes. Gas nozzle field quenching technique was chosen due to its advantages such as, symmetric cooling and ease of control.

2 EXPERIMENTAL PROCEDURE

2.1 Material and Production of Specimes

Initially, SAE 52100 steel (Table 1) was continuously cast into 265x265mm^2 billets. Then, following spheroidizing heat treatment, the billets were shape-rolled into 45mm diameter bars. Subsequently, a second spheroidizing treatment was done. Microstructures before and after this treatment are shown in Figure 1. Main advantage of the second spheroidizing is the improvement in machinability due to spheroidized carbides (Fe_3C and Cr_3C) in ferrite matrix.

Table 1. Chemical composition of SAE 52100 steel

Element	C	Si	Mn	P	S	Cr	Mo	Cu	Al
Wt%	0.97	0.21	0.44	0.011	0.007	1.51	0.05	0.11	0.006

Finally, long cylinders (L=200mm) of various diameters (D=10, 15, and 20mm) were machined from these bars. Samples were marked in such a way that their relative positions with respect to the initial bar are known exactly. The positions of the samples on the cross-sections are shown in Figure 2.

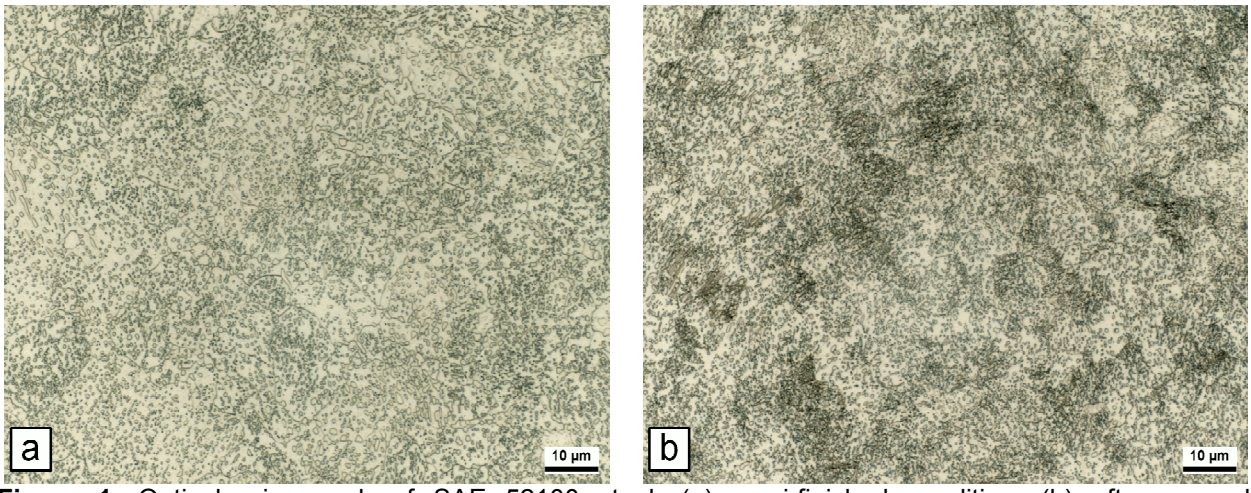

Figure 1. Optical micrograph of SAE 52100 steel: (a) semi-finished condition, (b) after second spheroidizing treatment.[7]

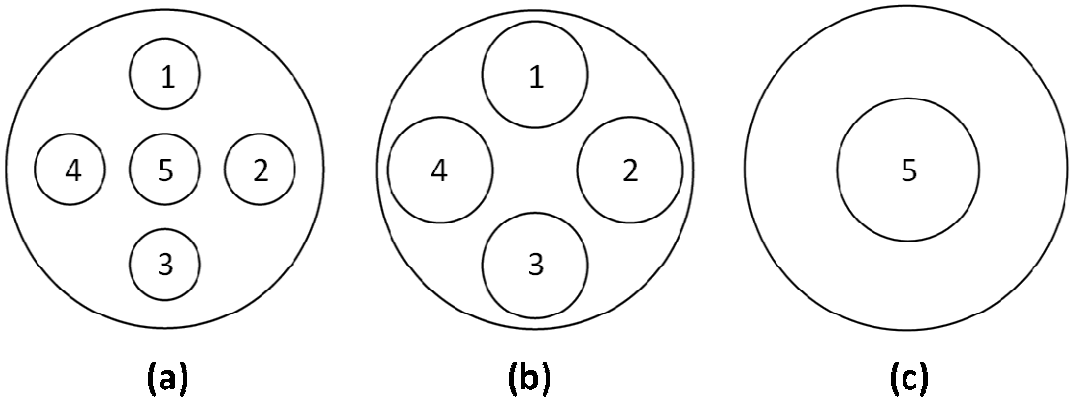

Figure 2. Machining positions of the samples with (a) 10mm (b) 15mm (c) 20mm diameters on the cross-section of the initial billet with 45mm diameter.

2.2 Experimental Setup and Procedure for Heat Treatment

Heat treatment setup consists of an atmosphere controlled vertical furnace and an optically-triggered gas nozzle field (Figure 3). The nozzle field is made up of four nozzle arrays that are located 90° to each other. Each array has 12 nozzles for nitrogen ejection. Mass flow controllers are connected to the pipes for feeding the nozzles. It has been recently proven that such a setup provides a very symmetric and controllable quenching.[8]

The cylinders were first heated and austenitized at 850°C in the preheated furnace under nitrogen atmosphere. Then, the specimens were immediately transferred to the gas nozzle field where they were quenched. Isothermal austenitization time for all specimens was 25 minutes, while the heating time was a function of the diameter to achieve equivalent austenitization conditions. The experiments were conducted according to Table 2 and each experiment was repeated at least five times to assure repeatability.

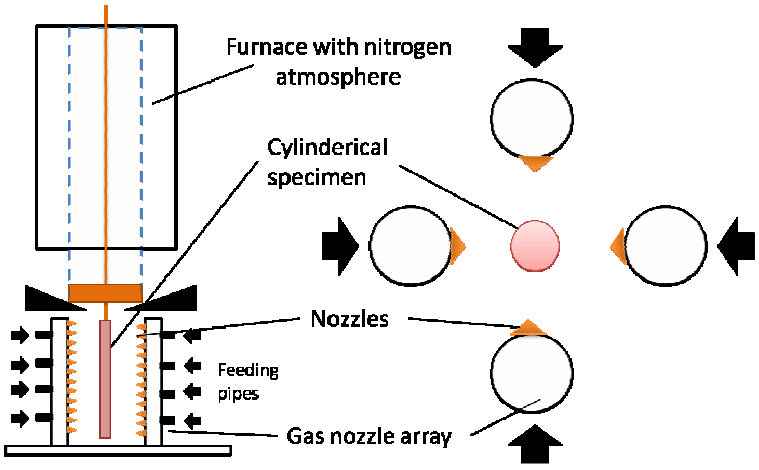

Figure 3. Heat treatment setup.

Table 2. Experimental window

		Cylinder diameter		
		10 mm	**15 mm**	**20 mm**
Total time in furnace	[min]	40	58	85
Gas velocity per nozzle	[l/s]	167	189	219
Heat transfer coefficient* (h)	[W/m^2K]	1250/1800	1250	1250/1400
Volume to surface ratio (V/S)	[m^3/m^2]	4.76	6.98	9.09
Biot number	[-]	0.15/0.22	0.23	0.30/0.33

Mean heat transfer coefficients which were determined by CFD calculations; In the calculations of Biot number average thermal conductivity of austenite is used. (λ_a =20.12 W/m K).*

2.3 Setup and Procedure of Coordinate Measurement

Coordinate measurements were performed before and after the heat treatment to determine dimensional changes using a contact based instrument (PRIMAR MX 4). Figure 4 illustrates the coordinate measurement strategy for calculation of dimensional changes for all components. Roundness plots at specified longitudinal positions were measured and circles were fitted to measured data in order to calculate the diameter change as a function of length. The length changes at the specified radial positions were computed by calculating the distance between fitted circles at the top and bottom surfaces.

Initial and final bending vectors were calculated from the projections of center of the fitted circles to the x-y plane (Figure 4a). Bending vector during heat treatment was determined by subtracting the initial bending vector from that after heat treatment (Figure 4b).

Distortion was investigated in terms of two aspects which were elaborated with respect to the position of the cylinders in the bar: dimensional changes (length, diameter and volume change), and shape changes (bending).

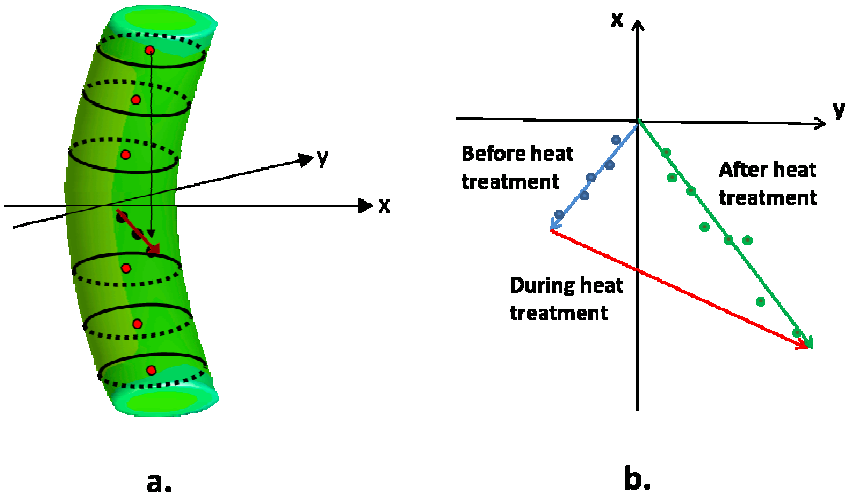

Figure 4. (a) Coordinate measurement procedure (b) Calculation of the bending vector.

The bending magnitudes of cylinders with different diameters are given with respect to Biot number:

$$Bi_a = \frac{h}{\lambda_a}\left(\frac{V}{S}\right) \quad (1)$$

where h, and λ_a are convective heat transfer coefficient and thermal conductivity of austenite, respectively, whereas V/S denotes volume to surface ratio.[9]

3 RESULTS AND DISCUSSION

3.1 Dimensional Changes

Relative dimensional changes of the samples which are representing different positions of the cross section of the initial billet are shown in Figure 5; namely, length ($\Delta L/L_o$), diameter ($\Delta D/D_o$), and volume change ($\Delta V/3V_o$).

It is clearly seen that dimensional changes deviate significantly with machining positions. It might be owed to the inhomogeneous distribution of Martensite start (M_s) temperature due to inhomogeneous distribution of Cr and C (Figure 7). It is a well known fact that M_s is a function of alloying elements. Various empirical equations to calculate M_s have been proposed considering C, Ni, Cr, Mo, Mn content.

For instance, the fraction of alloying elements for the specimens machined from the center of the billet (position 5) have less alloying elements in the parent phase due to core segregation, which eventually results in a higher average M_s. Consequently, a larger volume change occurs since they less retained austenite at the room temperature. However, it is not possible to make such deductions for other machining positions 1-4 by referring to Figure 5. Other reasons for the variation of the dimensional changes with respect to machining position might be the spatially asymmetric variation of material properties and the anisotropy in the transformation strain.[4] However, the justification of these assumptions requires additional dilatometer and mechanical tests.

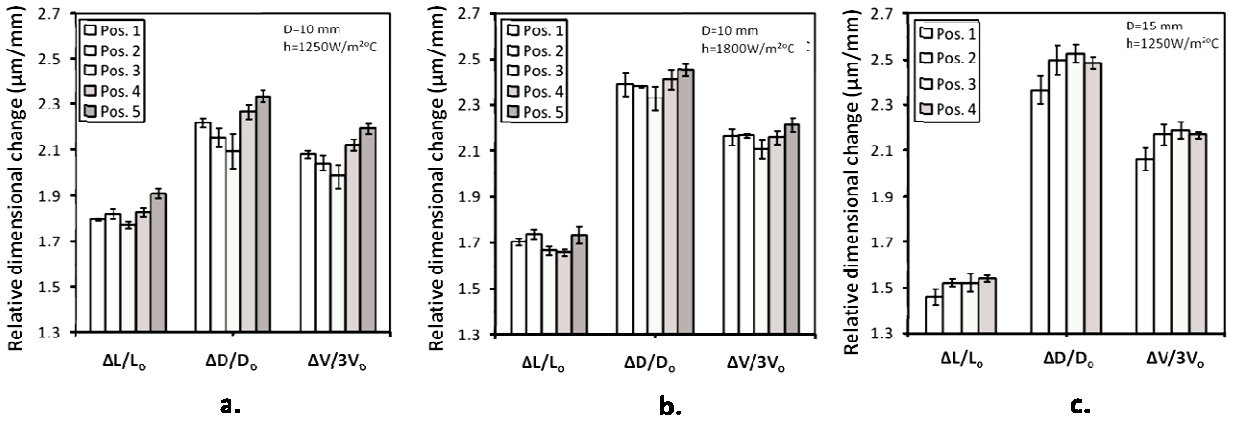

Figure 5. Relative dimensional changes of cylinder samples (a) D=10mm, h=1250W/m^2 K, (b) D=10mm, h=1800W/m^2 K, (c) D=15mm, h=1250W/m^2 K.

3.2 Shape Changes (Bending)

In Figure 6 bending magnitudes of cylinders with different diameters are given. There is no clear dependency of bending magnitude on diameter due to large scatter in the experimental data. In regards to the dependency of bending magnitude to the heat transfer coefficient for 20 mm diameter cylinders, the mean magnitude of the bending vector seems to increase slightly with increasing heat transfer coefficient. However, it is speculative to generalize this behaviour due to the large scatter in the results.

Summary of the bending directions from all experiments is presented on Figure 7 (b-c). In the figure, the magnitudes were magnified (x125) in order to improve visibility. The bending directions do not exhibit a distinct correlation with respect to machining position in contrast the findings of a similar study[4] on SAE 5120 (EN 20MnCr5) which revealed that the bending were correlated to the distribution of segragations. This seemingly contradictory result might be owed to the differences in the type of the inclusions (mainly Fe_3C/Cr_3C for SAE 52100 and $MnS/Fe_3C/Cr_3C$ for SAE 5120) and initial/final microstructures.

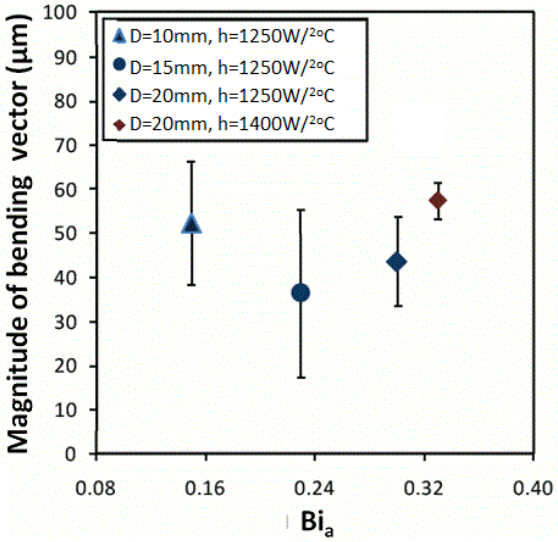

Figure 6. Magnitudes of bending vectors.

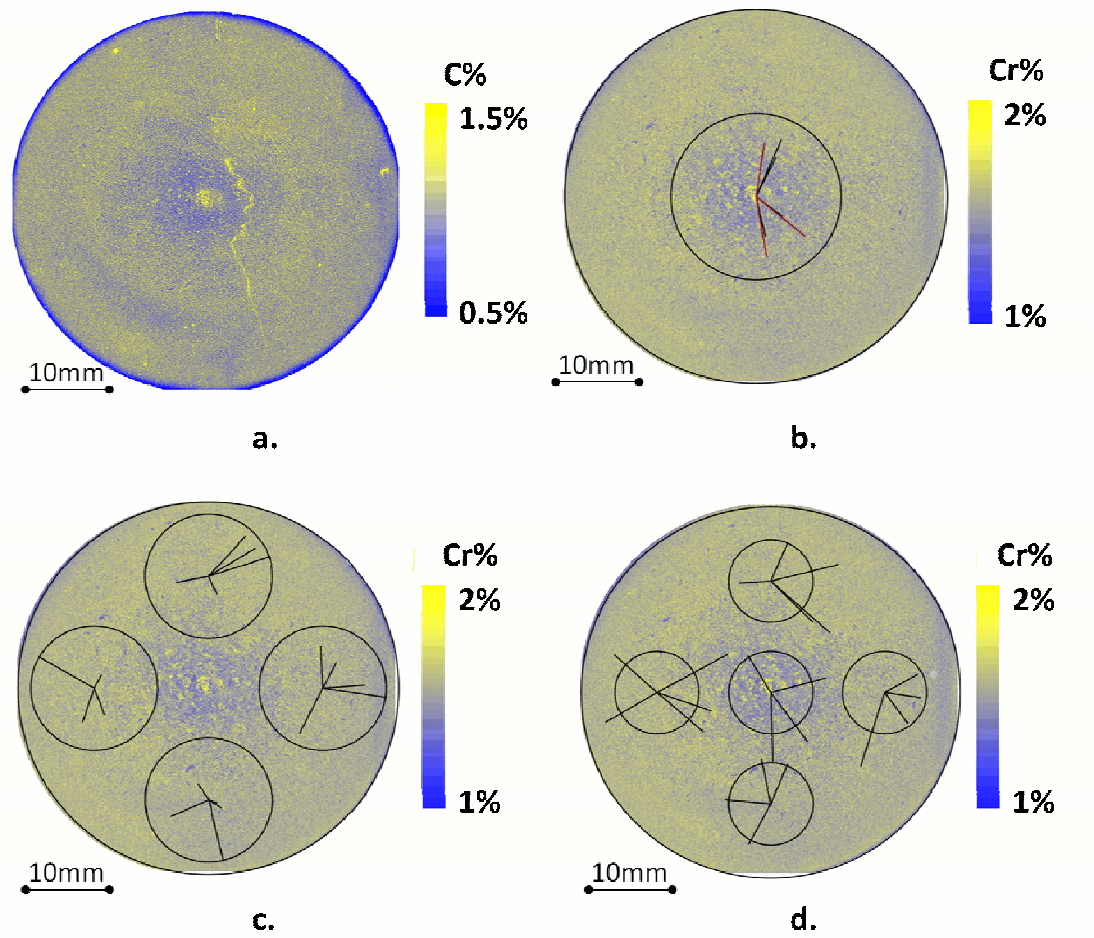

Figure 7. (a) C-distribution in the cross-section; and bending directions and magnitudes and Cr-distribution for (b) D=20mm, h=1250W/m^{2}K (black), h=1400W/m^{2}K (red), (c) D=15mm, h=1250W/m^{2}K, (d) D=10mm, h=1250W/m^{2}K.

In the former study on SAE 5120, the trend in the bending direction was explained by using the systematic distribution of anisotropic transformation strain (ATS) resulting from the development of banded microstructures during both heating and cooling. However, development of highly banded microstructure is not expected for SAE 52100 because of the following reasons:

- The initial microstructure consists of more or less randomly distributed spheroidized carbides without ferrite/pearlite, bainite/martensite bands. Consequently, ATS during heating is expected to be considerably low with respect to SAE 5120 for which early transformation of pearlite or bainite which results in rod-like growth of austenite.
- The final microstructure of SAE 52100 after quenching is mainly martensite with some retained austenite and negligible amount of bainite (at most 2%), whereas; the quenching results in a banded microstructure of bainite and martensite for SAE 5120. The ATS during quenching is also expected to be lower since the rod-like growth of bainite due to chemically banded microstructure is much likely than the rod-like growth of martensite.

- Chemical banding may not always result in strong microstructural banding. Low carbon steels with Mn are known to generate strongly banded microstructures.[3] At best of authors` knowledge, there is no such kind of report in the literature for high carbon steels with Cr as the main alloying element.

4 CONCLUSION AND OUTLOOK

In this study; the influence of the segregation structure on the distortion of SAE 52100 long cylinders was investigated by gas nozzle field quenching of cylinders which are machined at different positions in continuous cast and shape rolled bar. Following conclusions can be drawn according to the findings:

- Relative dimensional and volume change of long cylinders depend on the machining position, which is attributed to the inhomogeneous distribution of martensite start temperature due to inhomogeneous distribution of alloying elements.
- It is not possible to correlate the bending magnitude neither with diameter nor with the heat transfer coefficient due to large scatter in the results.
- Bending directions and magnitudes of SAE 52100 steels do not exhibit a distinct orientation relationship with microstructure, which might be owed to differences in the type of the inclusions and initial/final microstructures.

In the outlook of this study; it is necessary to perform dilatometer and mechanical tests at different positions of the bar in combination with microstructural investigations to reveal the spatial variations of the microstructure, martensite start temperature, anisotropic transformation strain and mechanical properties. Those points are under consideration of the ongoing research at IWT-Bremen to reveal the underlying reasons for this seemingly random behavior using both experimental and modeling/simulation tools.

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REFERENCES

1 Zoch, H.-W., Distortion engineering: vision or ready to application? 2nd International Conference on Distortion Engineering. Bremen, Germany, 2008. pp.13-20.

2 Clausen, B., Frerichs, F., Kohlhoff, T., Th, L., Prinz, C., Rentsch, R., Sölter, J., Surm, H., Stöbener, D., Klein, D., "Identification of process parameters affecting distortion of disks for gear manufacture Part I: casting, forming and machining", *Materialwissenschaft und Werkstofftechnik*, Vol. 40, No. 5-6, 2009, pp. 354-360.

3 Krauss, G., "Principles of Heat Treatment of Steel". Metals Park, Ohio: American Society of Metals, 1980.

4 Gür, C.H., Pan, J., Handbook of Thermal Process Modeling of Steels. CRC Press-Taylor&Francis Group, NY, 2009.

5 Hunkel, M., Hoffmann, F., Zoch, H.-W., "Simulation of the distortion of cylindrical shafts during heat treatment due to segregations", *Int. J. Microstructure and Materials Properties*, Vol. 3, No. 1, 2008, pp. 162-177.

6 Jaramillo, R.A., Lusk, M.T., Mataya, M.C., "Dimensional anisotropy during phase transformations in a chemically banded 5140 steel. Part I: experimental investigation", *Acta Materialia*, Vol. 52, No. 4, 2004, pp. 851-858.

7 Epp, J., Surm, H., Kessler, O., Hirsch, T., "In situ X-ray phase analysis and computer simulation of carbide dissolution of ball bearing steel at different austenitizing temperatures", *Acta Materialia*, Vol. 55, No. 17, 2007, pp. 5959-5967.

8 Frerichs, F., Lübben, T., Fritsching, U., Lohner, H., Rocha, A., Löwisch, G., Hoffmann, F., Mayr, P., "Simulation of gas quenching", *Journal de Physique. IV: JP*, Vol. 120, No., 2004, pp. 727-735.

9 Simsir, C., Lübben, T., Hoffman, F., "Prediction of distortions in through hardening of cylindrical steel workpieces by dimensional analysis", *Proceedings of New Challenges in Heat Treatment and Surface Engineering*, Dubrovnik, Croatia, pp. 351,358.