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CarboBain: Case Hardening by Carbo-Austempering – a short Introduction to Transformation Kinetics, Microstructure and Residual Stresses*

CarboBain: Einsatzhärten durch Aufkohlen und Bainitisieren – Ausgewählte Ergebnisse der Untersuchungen zur Umwandlungskinetik, des resultierenden Gefüges und der Eigenspannungen

Abstract/Kurzfassung

The beneficial strength properties of bainitic microstructures have been perceived since several years. The transformation kinetics and different morphologies of bainite were analyzed scientifically in depth and with increasing understanding the application of bainite is focus now. But still, bainitic microstructures are mainly utilized with chemically homogeneous steels. An application of bainitic transformed carburized samples is rather rare up to now. Therefore highly stressed geared components today typically are carburized and martensitically hardened. The microstructure in the case is generally composed of martensite with finely dispersed retained austenite and/or carbides. For gear wheel application during the past 50 years research was focused on topics like microstructure optimization within the bounds of martensite with no more than 25 % of retained austenite. For gears only very limited information on heat treatments with bainitic transformation of the case is available. In the USA few suppliers are propagating carbo-austempering heat treatment for case hardening applications [1]. In the literature a combination of carburization and austempering is discussed with only scarce data on material and microstructure performance [2-6]. To close the gap a systematic approach was made in a public funded project, analyzing transformation kinetics, microstructure properties and mechanical performance of two typical case hardening steels in carburized state being bainitic transformed. The heat treatment method using case hardening by carburization and adjacent austempering, the transformation behaviour, microstructure development and mechanical properties will be discussed. ■

Keywords: Case hardening, carbo-austempering, isothermal transformation, bainite, gear wheels

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Die vorteilhaften Festigkeitseigenschaften bainitischer Gefüge sind seit vielen Jahren bekannt. Die Umwandlungskinetik und daraus resultierende Morphologie des Bainits wurde durch vielfältige wissenschaftliche Untersuchungen zunehmend besser verstanden, sodass bainitische Gefüge heute in verschiedensten Anwendungsgebieten in den Fokus gerückt sind. Dennoch ist es bisher eher üblich eine bainitische Umwandlung an chemisch homogenen Bauteilen durchzuführen. Aufgekohlte und damit chemisch gradierte Proben werden eher selten bainitisch gehärtet. Infolgedessen sind hoch belastete Zahnräder nach Stand der Technik und Forschung heute überwiegend martensitisch gehärtet mit einem gut beherrschten Gefüge aus Martensit und fein dispersem Restaustenit. Daher ist die Anwendung einer isothermischen Umwandlung in Bainit im Anschluss an die Aufkohlung von Zahnrädern heute nicht Stand der Technik und nur sehr begrenzte Informationen zu Wärmebehandlung und Tragfähigkeit so behandelter Zahnräder sind verfügbar. Ferner sind nur wenige Anwender bekannt [1]. In der gängigen Literatur ist die Verfahrenskombination ebenso eher selten anzutreffen und nur mit begrenztem Versuchsumfang belegt [2-6]. Mit dem Ziel, diese Lücke zwischen dem Potenzial der Gefüge und den fehlenden Informationen zur Steuerung der Wärmebehandlung und den daraus resultierenden Festigkeiten zu schließen, wurde ein wissenschaftliches Vorhaben mit der Untersuchung der Umwandlungskinetik, des Gefüges und der verschiedenen werkstofftechnischen Kenngrößen wie Eigenspannungen und Härte gestartet. Einige ausgewählte Ergebnisse dieses Vorhabens werden im Folgenden dargestellt. ■

Schlüsselwörter: Einsatzhärten, Aufkohlen und Bainitisieren, isothermische Umwandlung, Bainit, Zahnräder

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1 Introduction

Typically case hardening includes a carburization of low carbon and low alloy steels in an oxygen bearing atmosphere at ambient pressure using carbon monoxide for carbon transfer or a pulsed hydrocarbon atmosphere (typically acetylene) at reduced pressure of less than 20 mbar for carbon transfer. After the designated carbon profile is set up during carburization, parts are typically quenched in a fluid or gaseous atmosphere at excess pressure to maintain a nearly complete martensitic transformation with fine disperse and metastable retained austenite. Adjacent to quenching, typically a tempering at moderate temperatures below 210 °C is applied to reduce martensite brittleness and increase stability of retained austenite or to diminish retained austenite.

The isothermal bainitic transformation (austempering) is known for many QT steel grades and cold working steels like bearing steels respectively and deemed to provide high hardness with better ductility than martensitic microstructures combined with a superior residual stress profile.

The combination of a carburization with a subsequent isothermal transformation into lower bainite has been used for few applications but not analyzed systematically, yet. Due to a patent by Caterpillar the process was protected from universal use until the end of 2007 [7] and only little scientific investigations were performed to increase knowledge on carbo-austempering. Therefore there is only limited data on transformation kinetics, microstructure and mechanical properties.

In 2012 a publicly funded scientific project was launched, to advance the process of carbo-austempering at the IWT Bremen. The results of the project are presented in the following paper.

2 Methods

Through carburization of samples was done by low pressure carburization, to avoid unwanted interference of the transformation behaviour due to inner oxidation in a RX-atmosphere. For carburization a two chamber IPSEN RVFOQ furnace with a Process-Electronic control system was used. The carbon content is set by a specific series of acetylene boost steps with adjacent diffusion steps and a final cooling to RT in the cooling chamber without oil quenching. To reduce carburization time and increase the quenching speed in dilatometer the samples were designed as hollow cylinders with an outer diameter of 4 mm and an inner diameter of 2 mm at 10 mm length. The samples were through carburized to a homogeneous carbon content in a range from 0.5 mass% of carbon up to 1.00 mass% carbon.

The carbon content or carbon profile was consequently analyzed using a calibrated S-OES device (spark-optical emission spectroscopy, Thermo Scientific ARL 3460). For the measurement of the chemical composition of the steels, for each element analyzed two calibrating standards were used to evaluate the correct numbers. For carbon profile measurement, the sample was ground to specific depth and subsequently analyzed with at least two standard samples for determination of the carbon content. Finally a discrete supporting point profile is achieved.

The transformation behaviour of the steels at certain carbon content was characterized experimentally using a Bähr DIL805A dilatometer with a quartz rod and inductive heating unit. To

achieve a comparable state of solution and distribution of carbon all samples in dilatometer were first austenitized at 940 °C for at least 10 min, then cooled to 840 °C and held for 15 min. Subsequently they were quenched with nitrogen gas at maximum cooling speed to RT for determination of martensite start temperature or quenched to isothermal holding temperature for transformation into bainite. After isothermal holding time had passed samples were cooled to RT and passed on to metallographic analysis.

2.1 Heat treatment of samples

The samples within the microstructure investigation were simple disc shaped samples of 30 × 30 × 8 in mm, which were carburized using a gas carburization process in a Solo202 Bell type furnace. Carburizing atmosphere is a RX-gas from methanol / nitrogen with propane.

The samples were first heated up to a temperature of 850 °C held for 30 min at a Cp of 0.6 %. Then the furnace heated up to 940 °C at Cp 90 % soot limit and carburized at a Cp of 1.15 % until 80 % of CD (carburization depth) is reached. Adjacent the Cp is reduced to an appropriate level for designated surface carbon content. Finally the temperature is reduced to 850 °C at a Cp according to the designated surface carbon content and a holding step for 30 min. is performed before quenching. Samples were quenched after carburization in a salt bath (AS140, no water addition) where to they were manually transported from the furnace. The aimed CHD for all samples was at least a CHD of 1 mm.

The gear wheels were carburized and austempered using the same method like applied to disc samples but with a reduced CHD requirement of 0.6 mm at a minimum.

Low pressure carburization was applied to some specific variants. Additionally for the LPC (low pressure carburization) carburized variants two different ways of austempering were applied:

The following procedure was applied to LPC samples with salt bath austempering. Therefore the samples were first low pressure carburized using a specific series of carburization boosts (acetylene) and diffusion segments. Afterwards samples were slowly quenched to RT and reheated for austenitizing at 850 °C (GS540 salt bath), held for at least 60 min and then transferred into a salt bath (AS140) for austempering. Austempering was performed at constant temperature for a defined duration (duration was determined by dilatometer tests).

For dry austempering experiments the samples were first low pressure carburized using a specific series of carburization boosts (acetylene) and diffusion segments. Afterwards samples were quenched to RT. Then the samples were reheated to 840 °C using a vacuum furnace and held for 30 min. Adjacent the samples were transferred internally into a quenching chamber where they were quenched in hot nitrogen to 220 °C and held for at least 90 seconds. Then the hot samples were transferred into a convection air furnace at 240 °C with a high gas speed of approx. 15 m/s.

2.2 Metallographic procedure and microstructure evaluation, hardness measurement

The metallographic investigation was performed by embedding of electric discharge wire erosion cut samples in EpoMet F/G (Buehler). If not stated differently all samples were ground and polished automatically and fine polished manually. Subsequently the microstructure was carved out by the use of alcoholic 3 % HNO₃

acid. The microstructure was documented using optical light microscopy. For special purpose some micro cuts were analyzed further using a SEM- secondary electron mode for increased magnification and in depth microstructure analyses.

Hardness measurements were performed using a Vickers hardness (HV1) measurement with automatic x-y-table for movement of the sample. All optical indentation measurements are performed automatically and are evaluated manually if automatic recognition had failed. All hardness profiles were measured on a flat polished metallographic micro cut.

2.3 Residual stresses and retained austenite determination (XRD)

Residual stresses and retained austenite were measured using a Psi-diffractometer with CrK α -radiation (35 mA / 35 kV). The residual stresses were calculated using the $\sin^2\Psi$ method with at least 15 χ -angles from -45° to 45° . The retained austenite content was calculated from the measurement of at least three ferrite and three austenite peaks. The profile was obtained from multiple chemical etching of the samples and repeated measurements. Maximum depth measured was approx. 1.5 mm.

2.4 4-Point-Bending-Experiments

Bending strength of carbo-austempered parts was measured using a universal tensile testing machine type SCHENK 250 with a specific experimental set up for 4-Point-Bending tests. The samples were equipped with strain gauges (type FLA-511) and samples' loading was measured using the load cell of the machine. The experiments were carried out using constant feed rates of 0.5 mm/min until the sample failed due to fracture. Supporting points of the bending bar

were at 90 mm distance on the lower side and 40 mm distance at the upper side. The effective lever arm was 25 mm.

The samples of a dimension (length \times width \times height) $100 \times 8 \times 10$ in mm were first gas carburized to a CD of approx. 1 mm and carbo-austempered in a salt bath (AS140) at constant temperature. Afterwards the sample was equally ground on both sides from a width of initially 8 mm to 5 mm to remove the carburized area and avoid the supporting effect. For application of the strain gauges a minimal polishing of the sample surface was performed, to remove the brittle oxide layer formed during transfer of the samples from carburizing furnace to the salt bath.

2.5 Tribological testing

Tribological testing and rolling fatigue testing was performed using a lubricated two disc wear test type Amsler. Two discs of different size are installed onto two shafts with 10 % difference of rotation frequency. By a combination of a 60 mm counter body (martensitic, high hardness) and a test sample with 25 mm diameter a slip of 46 % is established. The counter body has an axial radius of 5 mm and the test sample is flat. Therefore a point contact of both samples is present. Both samples are preloaded by a spring to achieve a Hertzian nominal pressure of $P_H = 2400$ MPa.

The tribological system is run lubricated using the high duty lubricant Mobilube HD 80W90 at 60°C which is injected into contact. Revolution speed is limited to 1500 Rpm during tests. The samples were meant to represent flank contact of gear wheels and therefore were ground before testing to remove IGO and reduce size and shape changes derived from heat treatment impacting contact area during testing. The tests were run for at least 44600 revolution of the test sample (3500 m). A verification of surface changes in the contact area was performed all 500 to 1000 meters.

	C	Si	Mn	P	S	Cr	Mo	Ni	Al	B	Cu	N
	Target values according to DIN 10084:2008											
DIN EN min	0.17	–	1.1	–	–	1.00	n.sp.	n.sp.	n.sp.	n.sp.	n.sp.	n.sp.
DIN EN max	0.22	0.40	1.4	0.025	0.025	1.30	n.sp.	n.sp.	n.sp.	n.sp.	n.sp.	n.sp.
	Sample analyses at the outer area of the rod											
Average	0.208	0.165	0.980	0.0141	0.0185	0.931	0.193	0.176	0.027	<0.0005	0.128	0.0097
Conf. Interv.	0.008	0.001	0.011	0.0007	0.0014	0.011	0.004	0.002	0.001		0.002	0.0005

Table 1. Chemical composition of EN20MnCr5mod, all given values in mass%

Tabelle 1. Chemische Zusammensetzung des 20MnCr5mod, alle Angaben in Masse-%

	C	Si	Mn	P	S	Cr	Mo	Ni	Al	B	Cu	N
	Target values according to DIN 10084:2008											
DIN EN min	0.15	–	0.5	–	–	1.5	0.25	1.4	n.sp.	n.sp.	n.sp.	n.sp.
DIN EN max	0.21	0.40	0.9	0.025	0.025	1.8	0.35	1.7	n.sp.	n.sp.	n.sp.	n.sp.
	Sample analyses at the outer area of the rod											
Average	0.198	0.180	0.530	0.0129	0.0021	1.672	0.300	1.518	0.034	<0.0005	0.118	0.0154
Conf. Interv.	0.004	0.001	0.003	0.0002	0.0003	0.016	0.003	0.018	0.001		0.001	0.0038

Table 2. Chemical composition of EN18CrNiMo7-6, all given values in mass%

Tabelle 2. Chemische Zusammensetzung des 18CrNiMo7-6, alle Angaben in Masse-%

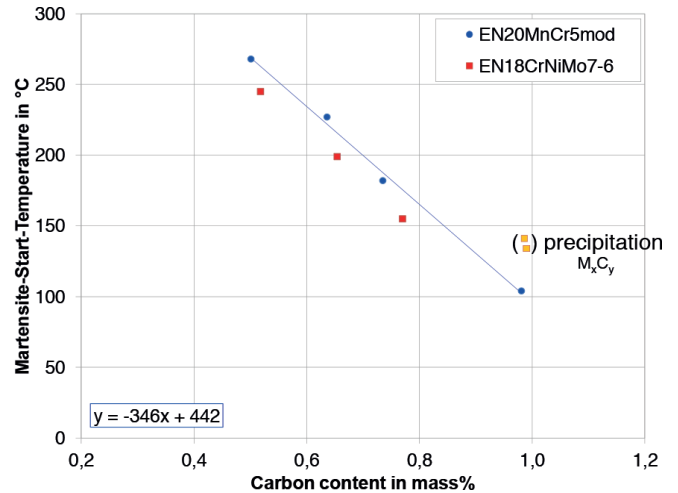
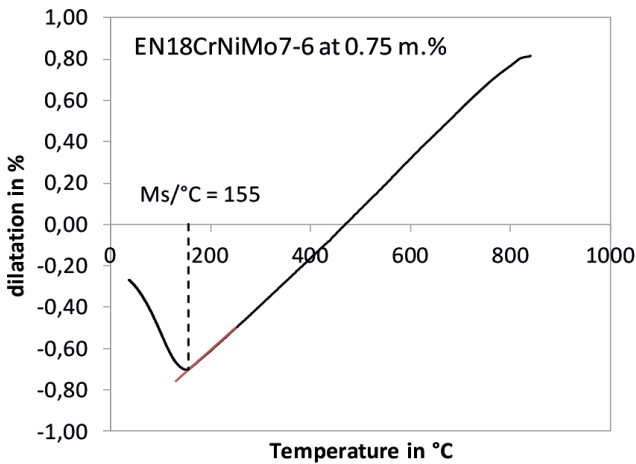


Fig. 1. Exemplarily dilatation plot and carbon dependent Ms temperature of both carburized steels EN20MnCr5mod and EN18CrNiMo7-6

Bild 1. Exemplarische Darstellung der Ms-Temperatur einer durchgekohten Dilatometerprobe und kohlenstoffabhängige Variation der Ms-Temperatur beider Stähle

3 Materials used

Tables 1 and 2 are showing the chemical composition of both utilized steels.

For all experiments two ferritic/pearlitic annealed case-hardening steels were used. The EN20MnCr5mod is a modified 20MnCr5, whose hardenability (HL-grade) was settled using molybdenum and by reducing the chromium and manganese content. The second steel is an EN18CrNiMo7-6 at high hardenability with a typical chemical composition.

4 Results – transformation behaviour

The transformation behaviour was studied using homogeneously carburized samples of EN20MnCr5mod and EN18CrNiMo7-6 at carbon contents of 0.5 mass%, 0.65 mass%, 0.75 mass% and

1.00 mass%. The procedure for heating and austenitizing was held equal for all samples. Firstly the carbon dependant martensite start temperatures were determined by quenching to RT.

Then the resulting M_s temperature was used to specify the isothermal holding temperatures for bainitizing, that were chosen 10 K, 20 K and 50 K above the corresponding M_s temperature. The results of the measurement are summarized in Figure 1. It can be seen, that there is a linear correlation of the M_s temperature with the carbon content in the analyzed range. For 18CrNiMo7-6 it was found, that with carbon content higher than 0.9 mass% the equilibrium carbon solubility limit a_{cm} is exceeded and undissolved carbides are present. Therefore the derived M_s temperature differs from the linear correlation. Beneath the variation of martensite start temperatures by carbon content a wide variation of bainitic transformation temperatures was explored. For a carbon content of 0.65 mass% the variation is shown in Figure 2. The isothermal holding temperature was varied from a temperature 10 K below M_s

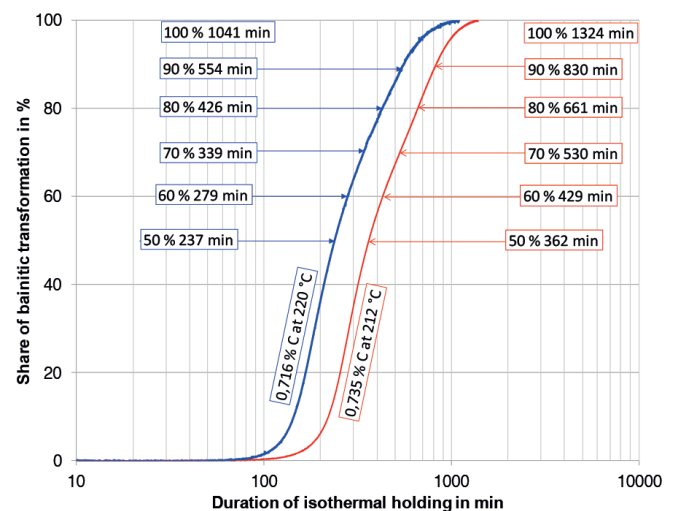
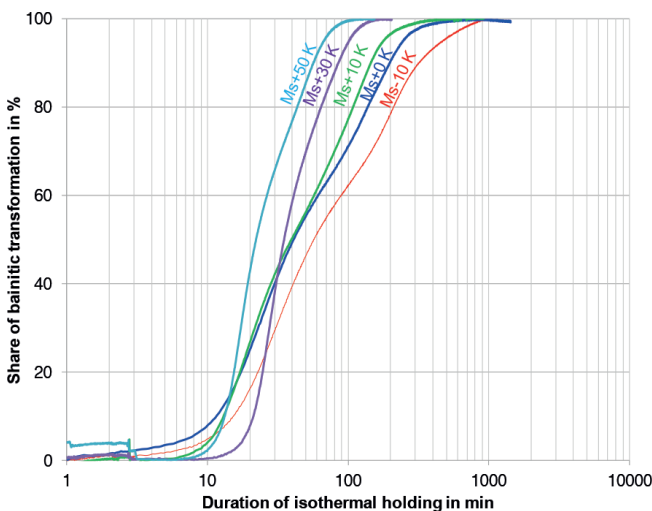


Fig. 2. Dilatometrically measured temperature-transformation curves of samples made of 20MnCr5mod with 0.65 mass% carbon content at different isothermal transformation temperatures (left) [8]. Transformation into bainite at M_s+30 K of samples made of 20MnCr5mod with slightly different carbon contents (right)

Bild 2. Mittels Dilatometer bei verschiedenen Umwandlungstemperaturen bestimmte und ausgewertete Zeit-Umwandlungsdiagramme von 20MnCr5mod Proben mit 0,65 Masse % Kohlenstoff (links) [8]. Einfluss leicht unterschiedlicher Kohlenstoffgehalte auf die Umwandlungskinetik (rechts)

to 50 K above M_s . The temperature impact on the transformation behaviour is, for transformation temperatures above M_s , quite easy to comprehend: with increasing temperature the transformation is sped up. At a second glance some specific effects are apparent: The incubation time for the bainitic transformation is shortened if the transformation is performed at a temperature in the vicinity of M_s . After approximately 50 % of the transformation being completed the speed decreases significantly and finally the expected order of transformation duration is reached until a nearly fully bainitic transformation is finished. At least there is a strong impact of stress and strains in the microstructure on the bainitic transformation kinetics. In the vicinity of the M_s , owing to the local deviating M_s temperature with segregations, small amounts of martensite are transformed, settling local stress and strain states speeding up transformation. After a progressive transformation the local stress state is altered and the transformation speed decreases due to the temperature and diffusion ruling the transformation. The impact of carbon on the transformation speed is displayed rather impressive in the right diagram of Figure 2. The deviation of 0.02 mass% of carbon already is impacting the transformation speed significantly.

Adjacent to the dilatometric austempering experiments the samples were analyzed further in a metallographic cut. Mainly the microstructure and the hardness were documented: From the variation of the carbon content and bainitizing temperature a set of hardness measurements obtained on the metallographic samples were available. In Figure 3 the hardness measured on the metallographic cuts of the samples with 0.65 mass% carbon transformed at different temperatures and the hardness of samples at different carbon content and transformation temperatures are shown. Basically it can be concluded, that hardness of the bainitic microstructure is increasing with decreasing transformation temperature. A transformation below M_s does not affect the maximum hardness anymore. Assumedly the tempered martensite is compensating the only slightly increased hardness of the bainite.

The microstructure (see Figure 4) is mirroring the increasing temperature morphologically: with increasing transformation temperature the morphology of bainite in light optical microscopy is looking slightly coarser and more structured. If the transformation is performed below the M_s temperature some initial martensite transformed prior to bainite, which is then tempered at transformation temperature, shows up. The early martensite appears in

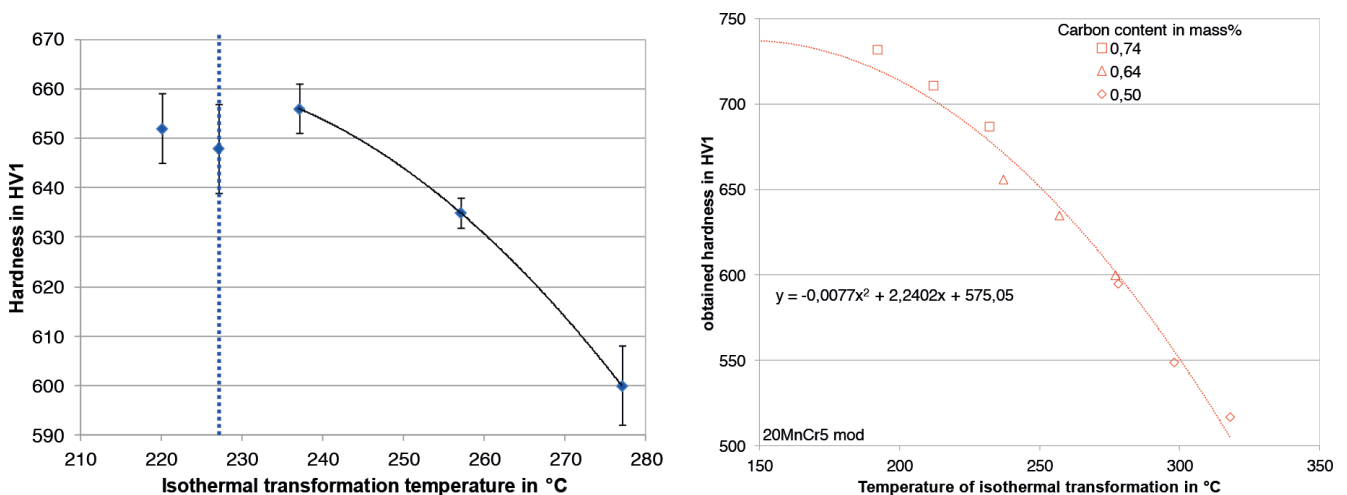


Fig. 3. Hardness of dilatometer samples made of 20MnCr5mod with 0.65 mass% carbon content isothermally transformed at different temperatures and dependency of the hardness of the bainitic microstructure, the carbon content and isothermal transformation temperature

Bild 3. Härte der Dilatometerproben aus 20MnCr5mod mit 0,65 Masse% Kohlenstoff nach isothermischer Umwandlung in Bainit bei verschiedenen Umwandelungstemperaturen (links). Abhängigkeit der erzielbaren Härte vom Kohlenstoffgehalt und der M_s Temperatur nach bainitischer Umwandlung (rechts)

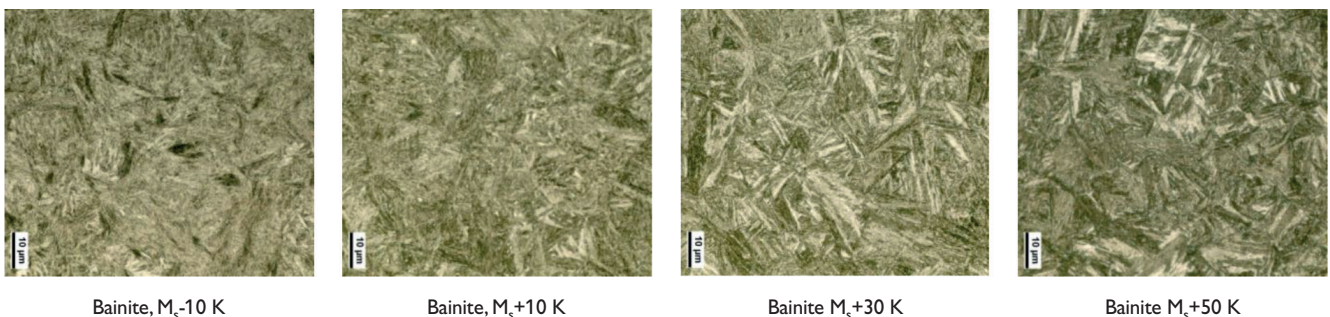


Fig. 4. Microstructure of the dilatometer samples made of 20MnCr5mod with a carbon content of 0.65 mass% and bainitic transformation between M_s-10 K (220°C) to M_s+50 K (277°C)

Bild 4. Gefüge im Lichtmikroskop verschiedener Dilatometerproben aus 20MnCr5mod mit 0,65 Masse-% Kohlenstoff nach Umwandlung bei um M_s liegenden Haltetemperaturen

the microstructure (see Figure 4 on the left) as dark etching spots in the microstructure.

With increasing carbon content, the M_s temperature is decreased allowing lower transformation temperatures and therefore higher hardness.

5 Results – microstructure and properties of samples with a carbon gradient

After the investigation of the transformation behaviour focus was laid on the investigation of the properties of carburized samples. To do so disc shaped samples of $\varnothing 30 \times 10$ in mm were carburized in a bell type furnace (Solo202 $300 \times 300 \times 300$ in mm) in a RX atmosphere generated from methanol and nitrogen. For austempering the carburized samples with a designated surface carbon content (Cs) from 0.5 mass% to 0.75 mass% and a CD of approximately 1 mm were manually taken from the furnace and transferred to a salt bath (AS140) at different transformation temperatures. Most samples were held for a fully bainitic transformation in the salt bath, but some were also extracted before bainitic transformation was completed, to study the partial bainitic microstructure and its properties.

An example of properties measured on a sample carburized to ~ 0.75 mass% of carbon and transformed in a salt bath at 240°C ($M_s+50\text{ K}$) for 320 min (90 % bainite) is given in Figure 5. The appearance of the hardness profile is comparable to the one derived from a martensitic transformation during a Q+T process, except of the plateau hardness, which is higher than a martensitic microstructure tempered at 240°C .

Owing to the gas carburization an IGO (intergranular oxidation) has occurred to a typical depth of 1/100 of the CHD. Counter applying a fast quenching in an oil bath, the transformation within the alloy depleted zone in a salt bath (no water added) is not a purely troostitic one. Some portions of ferrite can be seen. A hardness plateau of approximately half of the CHD was achieved at 670 HV1. The end of the plateau is at $CD_{0.3}$ and CHD is in the same

range of 1 mm as seen for typical Q+T processes. The microstructure is nearly fully bainitic with approximately 6 % of retained austenite and a small portion of martensite (see Figure 6). The carbon gradient is consistent with the end of the fully bainitic transformation. At approx. 0.6 mm depth the carbon content is reduced to 0.6 mass% raising the M_s temperature above bath temperature, producing a martensitic share in the microstructure being more susceptible to tempering during isothermal holding.

The most noticeable property of the sample was derived from XRD-measurements: the residual stress profile is rather outstanding for case carburized samples. Starting from a distance of $25\ \mu\text{m}$ below the IGO with tensional stresses of approx. 220 MPa, a compressive stress plateau of up to 400 MPa is stretched out into a depth of 0.5 mm. Adjacent a gradient to 280 MPa down to the CHD is present. Additionally only very little scatter of results could be found: the maximum standard deviation was 12 MPa even though not specifically longer measuring periods for each step were applied during diffractometer measurement. In Figure 7 the microstructure and the residual stress profiles of samples made of 18CrNiMo7-6 steel grade being carburized to a surface carbon content of 0.65 mass% with different CHD (1 mm and 1.3 mm) are presented. First it can be seen, that the microstructure is showing some banded line structure. The banded structure is derived from the segregations in the steel. Areas with increased alloy content have a retarded transformation kinetics compared to the lower alloyed zone and therefore are not fully transformed into bainite. Instead some martensite and retained austenite are present along with mostly bainite. The stress profile of this small disc shaped sample (diam. 30 mm and thickness of 8 mm) is showing that with increasing carburization depth and CHD the stress profile is following the hardness profile. Therefore there is a potential of transferring the results from smaller parts to bigger with increased CHD without losing the high compressive stresses in the case.

Light optical and scanning electron microscopy investigations finally showed, that for a carbon content of 0.65 to 0.95 mass% after an isothermal transformation into lower bainite at 240°C down to 160°C no significant changes in the morphology of the

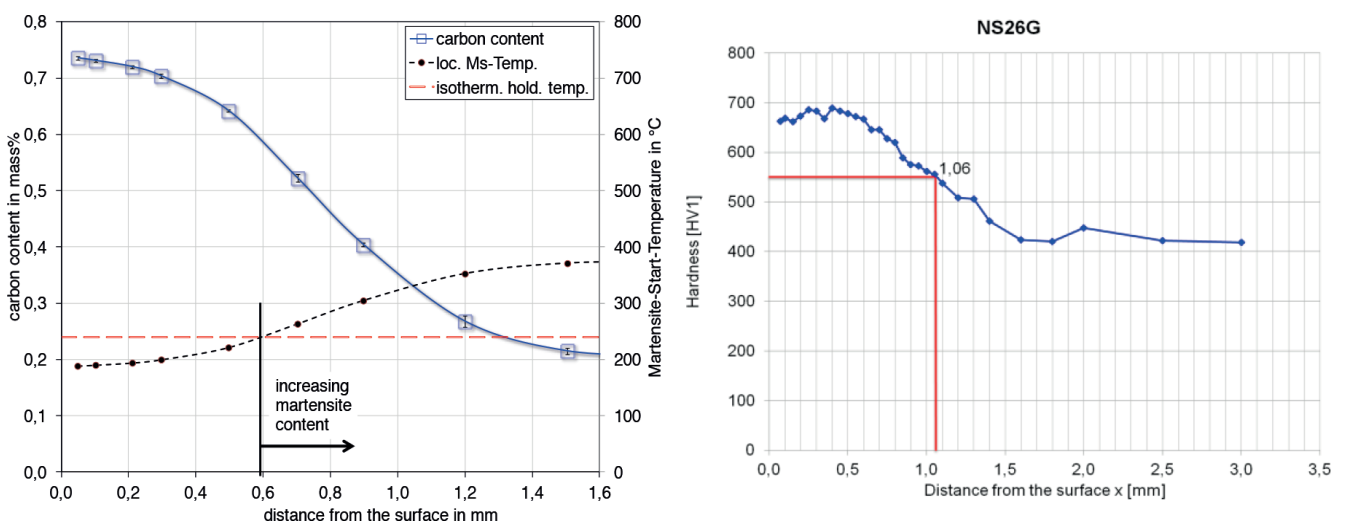


Fig. 5. Carbon profile and hardness profile of a sample transformed at 240°C ($M_s+50\text{ K}$) for 320 min

Bild 5. Kohlenstoffprofil und resultierende lokale M_s Temperatur (links) und resultierendes Härteprofil (rechts) einer Probe aus 20MnCr5 nach Aufkohlung und isothermischer Umwandlung im Salzbad für 320 min bei 240°C ($M_s+50\text{ K}$)

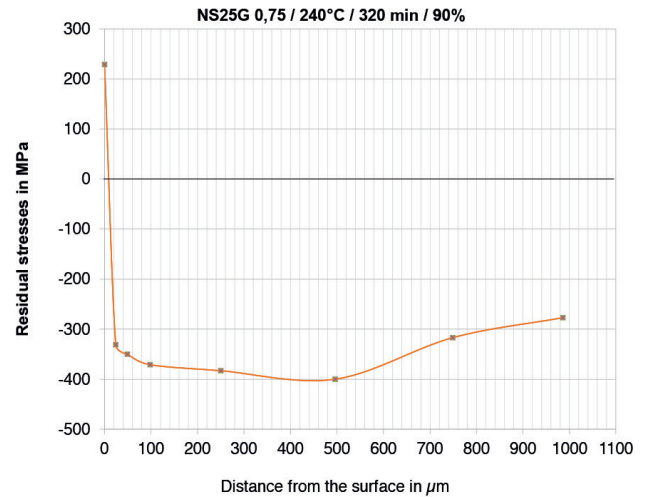
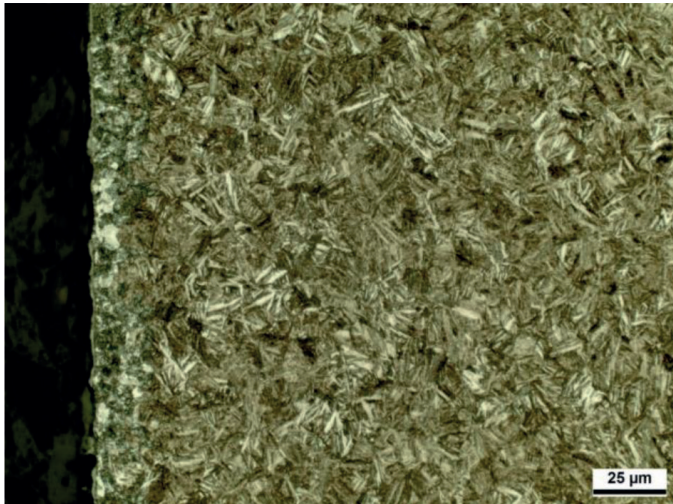


Fig. 6. Microstructure and residual stress profile of the sample made of 20MnCr5mod transformed at 240 °C (M_s+50 K) for 320 min

Bild 6. Gefüge und Eigenspannungen in der Randschicht einer aufgekohlten 20MnCr5mod Probe mit 0,75 Masse-% Randkohlenstoffgehalt und Umwandlung bei 240 °C (M_s+50 K) für 320 min im Salzbad (ca. 90 % Bainit)

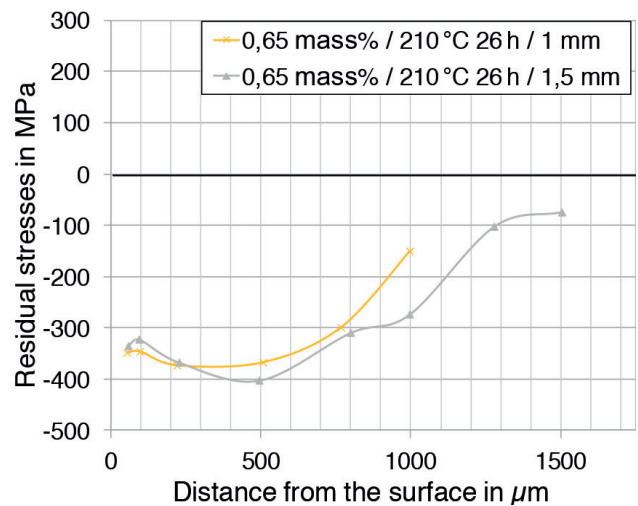
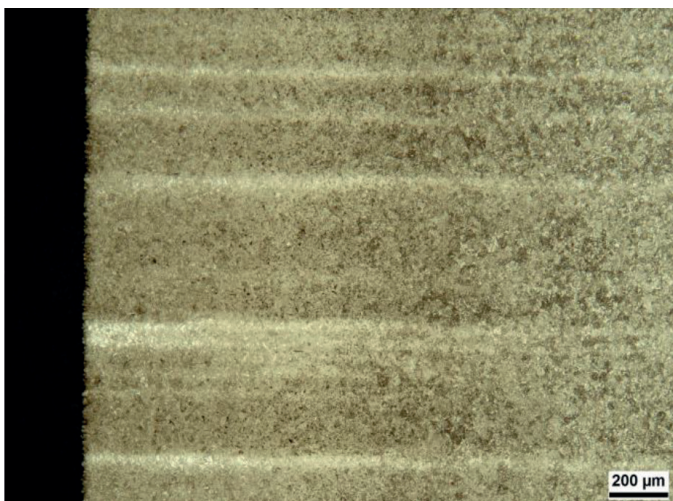


Fig. 7. Microstructure and residual stress profile of a sample made of 18CrNiMo7-6 with 0.65 mass% carbon transformed at 210 °C (M_s+30 K) for 26 h

Bild 7. Gefüge und Eigenspannungen in der Randschicht einer aufgekohlten 18CrNiMo7-6 Probe mit 0,65 Masse-% Randkohlenstoffgehalt und Umwandlung bei 210 °C (M_s+30 K) für 26 h im Salzbad bei verschiedener CHD

lower bainite could be found (see Figure 9). Nor did residual stress measurements indicate a significant impact of carbon content or transformation temperatures on the residual stress profile.

In Figure 8 the microstructure of a sample with 0.75 mass% of carbon in the surface and a transformation at 215 °C for 24 h into nearly 100 % bainite is shown. The pictures are taken at the metallographic cut in different depth (surface to core). The microstructure gradient being formed due to the carbon depth profile and the local M_s temperature is visible. A change of the mainly bainitic microstructure is getting visible from 800 μm on, where martensite content is increasing.

In Figure 9 three SEM microstructure pictures of carburized samples with different surface carbon content (0.95, 0.75 and 0.65 mass%) are shown. Even though the carbon content and transformation temperature are differing significantly (160 °C to

240 °C) the morphology of the lower bainite needle structure is rather similar. Due to carbon content and transformation duration at least a comparable amount and structure of carbides is formed within the bainitic plates.

6 Results – strength properties of carburized and bainitically transformed microstructures

6.1 4-point-bending test

The 4-point-bending tests were performed in a test machine (Schenck RM250) at constant speed with simple bending samples ($1 \times h \times d: 100 \text{ mm} \times 10 \text{ mm} \times 5 \text{ mm}$). Strain gauges were applied to log elongation of the samples in the loaded zone.

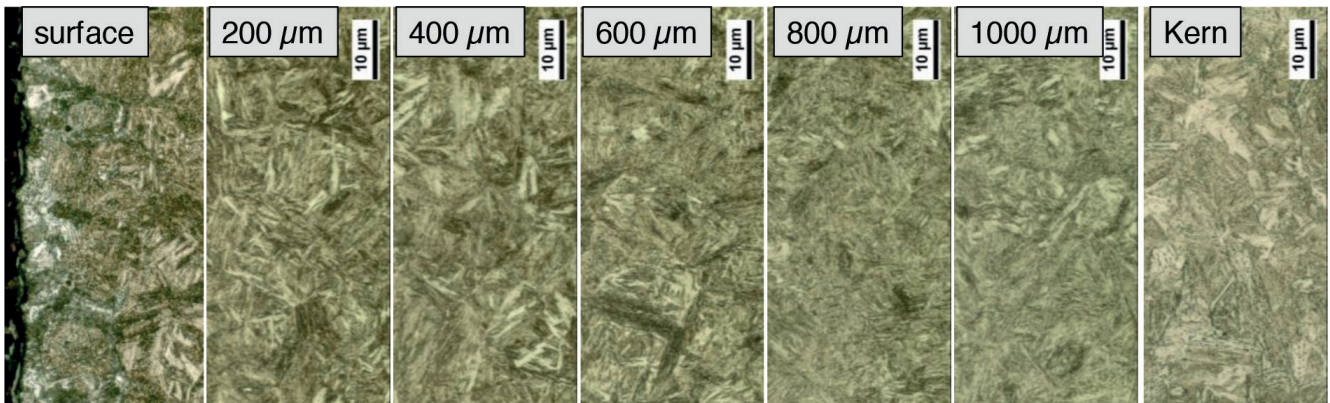


Fig. 8. Microstructure gradient in a EN20MnCr5mod sample at 0.75 mass% of surface carbon and 1 mm CHD transformed at 215 °C for 24 h (~100% bainite)

Bild 8. Gefügegradient einer 20MnCr5mod Probe mit 0,75 Masse % Kohlenstoff und einer HCD von 1 mm nach Umwandlung in ~100% Bainit bei 215 °C für 24 h

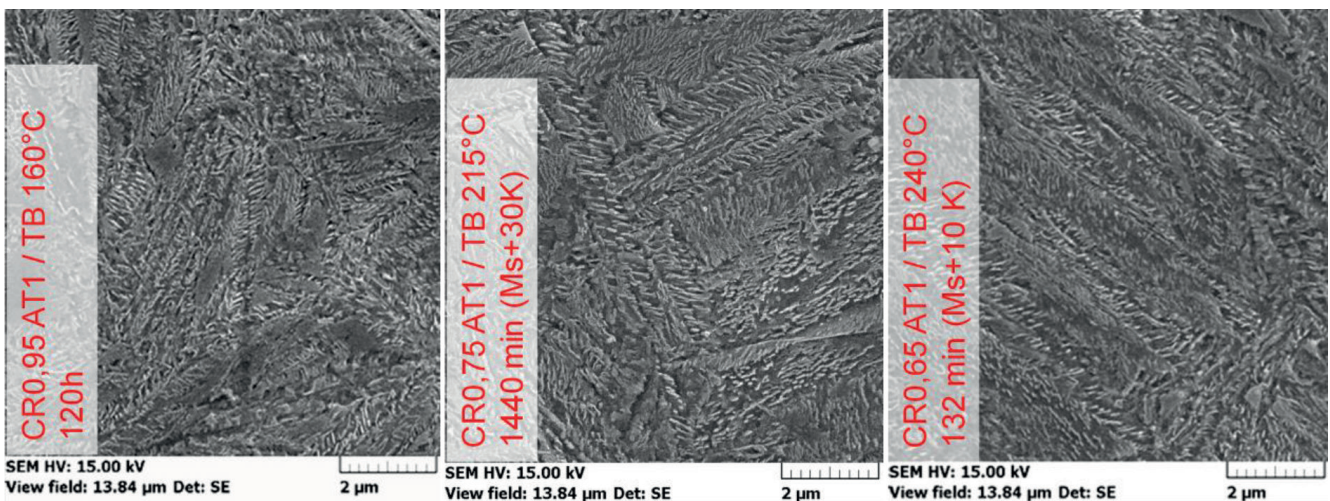


Fig. 9. HNO₃ etched microstructure (surface near) in SEM secondary electrons of three differently carburized and isothermally transformed samples (EN20MnCr5mod)

Bild 9. Mittels HNO₃-Ätzung im Rasterelektronenmikroskop sichtbar gemachtes Gefüge verschieden aufgekohlter 20MnCr5mod Proben in der oberflächennahen Randschicht

Many different heat treatment variations were tested, to get an overview of the influence of different bainitic treatments on the strength of the microstructure under static load conditions. Most samples were gas carburized and directly bainitically transformed in an AS140 salt bath at the specified temperature given in Table 3. The two variants called ND HG1 and ND HG2 were low pressure carburized, quenched, reheated to 840 °C and quenched in a high pressure gas quenching mode to approximately 220 °C, extracted and transformed in a furnace with circulated nitrogen (~15 m/s) at 240 °C for different durations. Additionally a reference variant of another project made of a 20MnCr5 which was gas carburized, oil quenched and tempered at 180 °C to a microstructure of martensite and retained austenite is included (last variant in Figure 10).

The derived results do not show significant changes of the yield strength due to changed surface carbon contents and isothermal holding temperature. At least this is in line with the observed small changes in the microstructure. The ultimate strength is showing some minor differences only. The highest strength was achieved with the variants B1 ND, B3 und B4. It can be assumed,

that with lower surface carbon content or a reduced IGO (intergranular oxidation) owing to the low pressure carburization a higher ductility and a reduced tendency of brittle fracture due to intergranular oxidation are the reasons for the good performance of these samples.

Comparing the elongation at fracture it can be said, that with increasing isothermal transformation temperature and decreasing carbon content, which both are indicating a lower hardness, an increased ductility can be achieved.

6.2 Gear wheel root load capacity of carbo-austempered spur gears

The mechanical properties of the microstructure were tested using different methods. Tribological testing and rolling fatigue testing was performed using a lubricated two disc wear test (Amsler, P_H = 2400 MPa, 46 % slip, Mobilube HD 80W90, 60 °C), where all bainitic variants did pass with very little damage comparably to the martensitic variants.

Finally the fatigue of carbo-austempered microstructures was tested using spur wheels with a modulus of 4 mm, teeth number of 24 and a gear width of 24 mm. Different heat treatment parameters were applied to the gear wheels to test their impact on tooth root fatigue by pulsator testing.

The gears were tested at the FZG gear research centre at the Technical University of Munich. The gears were heat treated with the parameters given in Table 4. Most variants were directly quenched after gas carburization in a salt bath and left there for bainitising for the given duration. Few were post processed

Variant	Specification	Grade
B1	Gas-carburizing $C_S = 0.75$ mass%; Salt bath 215 °C 24 h; 100 % bainite	20MnCr5mod
TB3	Gas-carburizing $C_S = 0.75$ mass%; Salt bath 215 °C 13 h 45 min; 90 % bainite	
TB2	Gas-carburizing $C_S = 0.75$ mass%; Salt bath 215 °C 8 h 50 min; 70 % bainite	
TB1	Gas-carburizing $C_S = 0.75$ mass%; Salt bath 215 °C 6 h; 50 % bainite	
B1 ND	LPC $C_S = 0.75$ mass%/Salt bath 850°C Salt bath 215 °C 24 h; 100 % bainite	
B2	Gas-carburizing $C_S = 0.75$ mass%; Salt bath 240 °C 6 h; 100 % bainite	
ND HG1	LPC, double hardening, $C_S = 0.75$ mass%; Hot gas 240 °C 10 h 40 min; 100 % bainite	
ND HG2	LPC, double hardening, $C_S = 0.75$ mass%; Hot gas 240 °C 4 h 10 min; 70 % bainite	
B3	Gas-carburizing $C_S = 0.65$ mass%; Salt bath 240 °C 3 h 50 min; 100 % bainite	
B4	Gas-carburizing $C_S = 0.52$ mass%; Salt bath 280 °C 40 min; 100 % bainite	
B5	Gas-carburizing $C_S = 0.65$ mass%; Salt bath 210 °C 26 h; 100 % bainite	18CrNiMo7-6

Table 3. Heat treatment variants tested in 4-point-bending test

Tabelle 3. Variantenplan der 4-Punkt-Biegeversuche

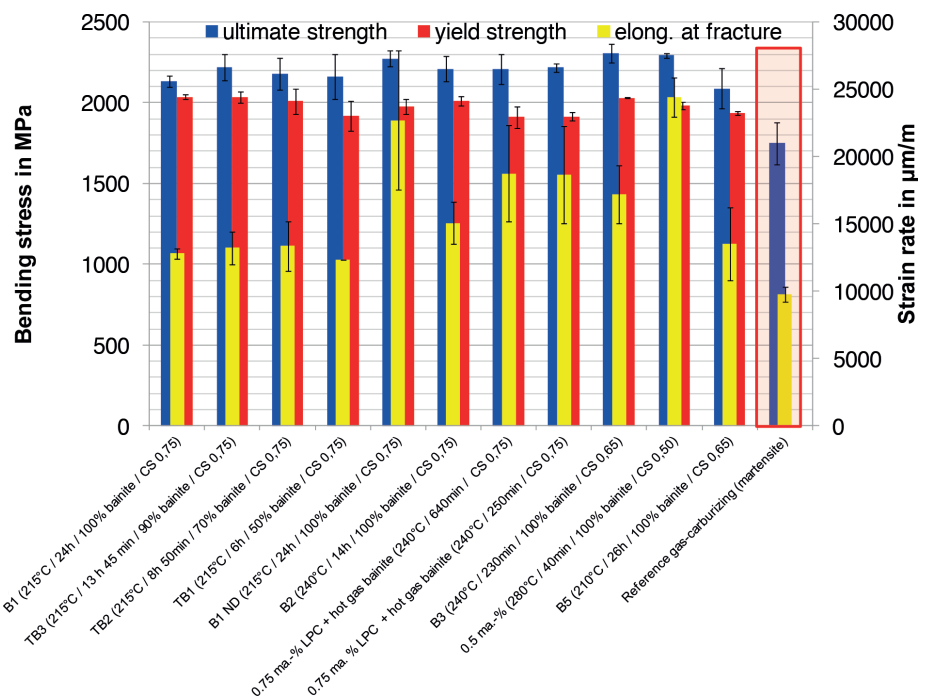


Fig. 10. Results of the 4-point-bending tests

Bild 10. Ergebnisse der 4-Punkt-Biegeversuche

Variant	Heat treatment parameters and post processing	Material
B1	0.75 mass% C; 215 °C 24 h;	~100 % Bainite
B1 EA	0.75 mass% C; 215 °C 24 h;	~100 % Bainite; electrolyt. polished (~25 µm)
B1 KG	0.75 mass% C; 215 °C 24 h;	~100 % Bainite; shot peened
B3 ND+	0.65 mass% C; 215 °C 24 h;	~100 % Bainite; LPC + single hardened
B2	0.75 mass% C; 240 °C 14 h;	~100 % Bainite
B3	0.65 mass% C; 240 °C 3 h 30 min;	~100 % Bainite
TB2	0.75 mass% C; 215 °C 8 h 50 min; 180 °C 2 h;	~70 % Bainite
B5	0.65 mass% C; 210 °C 26 h;	~100 % Bainite
		18CrNiMo7-6

Table 4. Spur gear austempering variants for root load capacity testing

Tabelle 4. Zahnradvarianten für die Zahnfußbiegeprüfung im Pulsator

by shot peening (B1KG) or electrolytical removal of the IGO (B1EA). One variant was low pressure carburized and cooled to RT, afterwards these gears were austenitized in a GS540 salt bath at 850 °C for 1 h and austempered in a salt bath 10 K below Martensite-Start (B1ND) to a fully bainitic microstructure.

In Figure 11 the results of pulsator testing at the FZG are shown in the tooth root fatigue diagram according to ISO 6336 [9]. It can be seen, that the IGO and the succeeding non martensitic transformation at the very surface of the gear wheels strongly limits the fatigue strength.

By electrolytic polishing (B1 EA) or LP-carburization (B3 ND+) IGO could be eliminated or reduced and good strength properties of the tooth root fatigue were revealed. By shot peening without removing surface damage superior strength properties could be attained. At least carbo-austempered gears did show very good mechanical properties but also

did show some scatter of results, being most likely driven by segregations and locally differing microstructure and strength of the material.

7 Summary

Carbo-austempering of case hardening steels is a new robust variant of the classical case hardening process, proceeding parts after carburization in a salt bath for isothermal transformation into lower bainite. The transformation behaviour into lower bainite of both case hardening steels was studied in a wide range of parameters inclining a variation of carbon content from 0.5 to 1.0 mass %. For gear wheel application typically a minimum hardness of 650 HV1 is required. Additionally the duration of transformation should be less than 24 hours for practical reasons. Therefore the range of parameters could be narrowed to a carbon content of min. 0.65 mass% and a transformation temperature of / and less than 240 °C to meet the requirements. A carbon content of 0.75 mass% and a transformation at 215 °C was setting the limit for duration for the EN20MnCr5 mod.

The investigation of carbon profiles produced by gas carburization and analysis of the microstructure did not reveal strong deviations of the morphology of the investigated lower bainite range. From the heat treatment a superior residual stress profile could be attained.

The mechanical properties did not show strong impact of the isothermal holding temperature nor of the surface carbon content. But internal oxidation revealed to diminish fatigue strength of spur wheels. The static strength (4-P-bending) of carbo-austempered specimens exceeded the typical case hardening specimens and tribological performance was equal for bainitic and martensitic samples. The tooth root fatigue limit of carbo-austempered gears showed good results, being competitive with those of case hardening steels with martensitic microstructure. Nonetheless the bainitic microstructure is bearing the potential of improved temperature stability.

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The IGF Project 17661 N of the research association *Arbeitsgemeinschaft Wärmebehandlung und Werkstofftechnik e. V. (AWT)* was

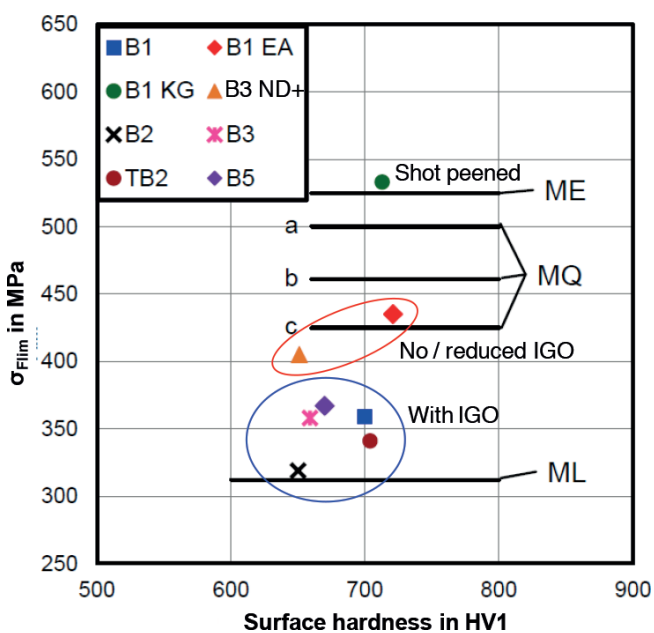


Fig. 11. Tooth root fatigue limits classified in the tooth root fatigue chart of ISO6336 [9]

Bild 11. Einordnung der geprüften Zahnfußbiegefestigkeit $\sigma_{F_{lim}}$ im Schaubild der ISO6336 [9]

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Neues Stahleisen-Prüfblatt

Stahleisenprüfblatt SEP 1571 – Bewertung von Einschlüssen in Edelstählen auf Basis der Einschlussflächen
 1. Aufl., Oktober 2017, Verlag Stahleisen GmbH, 48 Seiten, auch als pdf verfügbar, komplett (Teil 1-3): 99,00 €, Teil 1: 75,00 €, Teil 2: 25,00 €, Teil 3: 25,00 €, Tafel zum SEP 1571 (Hilfstabelle zur Klassifizierung): 20,00 € – Artikelnummer: 31571, www.stahleisen.de

In dieser Prüfvorschrift wird grundsätzlich die Prüfung von Edelstählen auf nichtmetallische Einschlüsse in Form von Sulfiden und Oxiden im Anschliff beschrieben. Die Prüfung kann manuell und automatisiert mithilfe von Bildanalyse-Systemen erfolgen. Zwischen den manuell und den automatisiert ermittelten Ergebnissen sollte sich kein

größerer Unterschied ergeben als zwischen zwei unterschiedlichen Prüfern aus unterschiedlichen Laboratorien. Dazu folgen die Einstufungen einer mathematischen Systematik. Regeln zur Zusammenfassung und zum Unterscheiden von Einschlüssen sollen für die manuelle und für die automatisierte Bewertung keinen Interpretationsspielraum lassen.

Inhalt:

Teil 1: Grundlagen – Probenahme, Schliffvorbereitung und Prüfbericht – Teil 2: Verfahren K und M – Prüfumfang und Auswertung der Verfahren M (Maximalwert) und K (Mittlerer Einschlussgehalt) – Teil 3: Verfahren E – Prüfumfang und Auswertung des Verfahrens E (Extremwertanalyse)