Continuously cooled bainitic steel HSX®Z12: one decade of experience

H. Roelofs, St. Hasler, U. Urlau, M.I. Lembke, G. Olschewski

4th Int. Conf. On Steels in Cars and Trucks, 2014
Continuously cooled bainitic steel HSX®Z12: one decade of experience

H. Roelofs, St. Hasler, U. Urlau, M.I. Lembke, G. Olschewski

Reducing the weight of car components has led to more filigree parts and the use of stronger materials. Conventional solutions with quench and tempered steels not always fulfil the wishes concerning technical reliability, economics and environmental friendliness. Continuously cooled bainitic steels like HSX®Z12 [1] are sometimes clearly better balancing these aspects which has led to a successful introduction into car components during the last decade. To reduce the initial lack of experience the realization of real industrial parts was accompanied by numerous research projects from the beginning. Besides basic steel characterization (microstructure, toughness, static and dynamic strength) and optimization of production parameters (hot rolling, straightening, bright bar production) also subsequent operations like machining, welding, nitriding were considered in detail.

Steel design

Non heat treated high-strength steels (like ETG®) as alternatives to quench & tempered steels are a core competence of Steeltec. Moving to strength levels above 1'000 MPa continuously cooled bainitic steels came into consideration at the end of '90 and early '00. With the focus on costs the decision was made to concentrate first on upper bainitic microstructures that could be reached directly from the rolling mill without adding a high quantity of expensive alloying elements to the steel composition.

Table 1 shows the range for the chemical composition considered for material design.

<table>
<thead>
<tr>
<th>element</th>
<th>range</th>
<th>focus</th>
</tr>
</thead>
<tbody>
<tr>
<td>carbon</td>
<td>0.15 – 0.25 %</td>
<td>no ferrite, but not too hard</td>
</tr>
<tr>
<td>silicon</td>
<td>0.80 – 1.30%</td>
<td>avoiding carbide formation</td>
</tr>
<tr>
<td>manganese</td>
<td>1.30 – 1.70%</td>
<td>taking care of segregation</td>
</tr>
<tr>
<td>chromium</td>
<td>1.00 – 2.00 %</td>
<td>adjusting phase transformation</td>
</tr>
<tr>
<td>molybdenum</td>
<td>0.10 – 0.40 %</td>
<td>avoiding temper embrittlement</td>
</tr>
<tr>
<td>sulphur</td>
<td>0.10 – 0.20 %</td>
<td>improving machinability</td>
</tr>
<tr>
<td>boron</td>
<td>not compatible with sulphur</td>
<td></td>
</tr>
</tbody>
</table>

Table 1 Alloing elements considered for steel design

Constant properties in the diameter range from Ø18 to Ø60 mm were required for rolled bar products. Although a fine homogenous microstructure was reached from the beginning on with small diameters (Fig. 1a), large bar diameters (and low cooling rates) first exhibited a bainitic microstructure mixed with coarse phases of ferrite and martensite (Fig. 1b.). Several modifications of steel composition were necessary to guarantee a fine and homogenous structure for large diameters.
Today the peeled bainitic long product HSX\textsuperscript{®}Z12 is used in several automotive applications such as pressure loaded mechanical parts e.g. for camshaft adjustment or in highly oscillated regions like the suspension strut.

![Figure 1](image1.png)

**Fig. 1**
LOM picture of bar cross sections (position R/2)

- a. \(\Phi22\) mm bar, start-up period
- b. \(\Phi55\) mm bar, start-up period “coarse structure”
- c. \(\Phi52\) mm bar, this year “fine structure”

**Contribution of phases**

To quantitatively analyze phases scanning electron microscopy (including high resolution FEG-SEM) and X-ray diffraction were performed at the CENIM in Madrid. Bainitic steel HSX\textsuperscript{®}Z12 in the peeled and straightened condition exhibited \(~70\%\) of granular bainite, \(~15\%\) of retained austenite, \(~15\%\) of martensite and \(<1\%\) of ferrite (in the vicinity of manganese sulphide inclusions).

![Figure 2](image2.png)

**Fig. 2**
In this high resolution FEG-SEM picture after Nital etching the martensite and austenite constituents show up as bright phases. Their sizes are in the order of magnitude of 1 \(\mu\)m. The dark grey matrix is bainitic ferrite. Very fine inclusions can be seen within the bainitic matrix. From thermodynamic calculations the formation of chromium carbides is suggested.
Structural banding

Steels with elevated manganese and chromium contents show structural bands after etching. This is due to local segregations in these elements and often observed for quench & tempered steels.

After etching a banded microstructure is visible in the LOM. The investigation of banding was performed to see whether particular features influence mechanical properties. However, going to large magnifications with FEG-SEM the bands almost disappeared. The morphology of the microstructure obviously did not change between matrix and bands [2].

One possible explanation for this behaviour was found in concentration maps determined by electron microprobe analysis (EMPA). Fig. 5 shows the local distributions of Si, Mn and Cr, in a longitudinal steel sample (Ø 32 mm bar). Within the bands Si and Cr were enriched, on the contrary Mn was depleted. This was a quite surprising result. Similar bainitic steels with low sulphur content (like HSX130®HD) exhibited Mn enriched bands instead.
The reason for this exceptional behaviour is still under investigation. The decomposition in Cr and Mn supposedly occurred during the solidification process. Passing the two phase regime of $\delta$-ferrite and austenite Cr preferred to stay in the $\delta$-ferrite, whereas Mn favoured austenite. Simultaneously formed manganese sulphide inclusions seemed to interact with this decomposition process. Although details are not completely understood the consequence is obvious. The depletion in Mn partly compensated the elevated amounts in Cr and Mo in the bands. Hence the phase transformation in the bands did not significantly differ from that in the matrix. Morphologically and crystallographically bands and matrix are not distinguishable and therefore not visible by applying FEG-SEM or EBSD.

Retained austenite

Steel with the above mentioned compositions are known as TRIP-assisted steels with a certain amount of retained austenite. During processing (straightening, drawing, stress relieving) a part of the retained austenite can transform into martensite (TRIP effect). Producing bright bars these effect must be mastered.

Quantitative analysis of the retained austenite (RA) was done by X-ray diffraction of a $\varnothing32$ mm hot rolled bar. In fig. 6 measured values at three positions (center, mid-radius and near surface) were shown in the as hot rolled condition as well as after peeling/straightening (tradename HSX® Z12) or drawing/straightening (tradename HSX® 130). During “peeling/straightening” the amount of RA drops by ~3%. A decrease in the order of ~8% occurs during drawing.
The amount of RA is lowest at the near surface position. To investigate this in more detail surface layers were electrochemically eroded step by step to get a depth profile of RA content of steel HSX®Z12. In addition residual stresses were measured (sin²ψ method). Within a layer of 500 μm below the surface a significant amount of RA was transformed to martensite. The corresponding volume changes led to surface compression stresses in the order of several 100 MPa.

Depending on customer’s needs optimization of straightening parameters and additional stress relieving treatments might be essential to control surface stresses and to ensure satisfying results.

**Nitriding /nitrocarburizing**

 Bainitic structures are formed at temperatures between 600 and 500°C. Nitriding and nitrocarburizing is performed just in the same temperature regime. The question arose whether tempering effects decrease the strength level of such steels more than ferritic-pearlitic steels.

At the IWT in Bremen two nitriding and two nitrocarburizing conditions were applied using Ø45 mm samples from drawn bars:
• nitriding at 520°C with $K_N = 2$ during 10 hours
• nitriding at 520°C with $K_N = 2$ during 40 hours
• nitrocarburizing at 570°C with $K_N = 2 + 2.5\% \text{CO}_2$ during 0.5 hours
• nitrocarburizing at 570°C with $K_N = 2 + 2.5\% \text{CO}_2$ during 4 hours

In all cases compact and regular compound layer could be formed. As an example the compound layer after nitrocarburizing for 4 hours at 570°C (~9 μm) is shown in Fig. 8. Diffusion layers and corresponding nitriding hardness depths were similar to them of reference steels 44SMn28 (ETG) and 38MnVS6. A selection of results can be found in [3]

![Fig. 8 LOM picture of compound layer](image)

![Fig. 9 Proof stress before and after Nitrocarburizing (mid-radius)](image)

Fig. 9 shows the drop in proof stress $R_{p0.2}$ of drawn bainitic HSX-steel during nitrocarburizing (4h at 570°C). This was measured in a mid-radius position (bulk). The same reduction of 20 – 25% in $R_{p0.2}$ was found for 44SMn28 and 38MnVS6 in as drawn conditions. This indicates that a part of the work hardening (from drawing) was reversed. However, significant changes in the microstructure of the steels (like carbide formation) were not observed.

**Machinability**

*Increasing the strength level of values between 1‘100 and 1‘300 MPa the productivity of machining processes will decrease. This is well known from various classes of steel. Therefore Steeltec decided at an early stage of development to ease machinability by sulphur addition. The efficiency of 0.15% sulphur in steels with the considered strength level was not known from the beginning on.*

Most of today’s knowledge concerning machining HSX®Z12 came from customers producing parts. Systematic investigations of drilling and deep hole drilling at the IWF/ETH in Zürich accompanied this early learning phase [4]. Later turning tests at the ISF of TU Dortmund completed “the picture” [4]

Today’s experiences with variants of HSX and with Q&T steels can be summarized as follow:
• Increased impact toughness leads to thicker chips and higher cutting forces
• Sulphur addition tends to decrease chip thickness (lowering cutting forces)
• Chip breakage is eased by sulphur addition
- Tensile strength can be increased by drawing (HSX®130) without increasing the resulting cutting forces in turning.

As an example tool lifetime investigations were performed in comparison to 38MnVS6 and conventional Q&T steels. The time dependence of cutting forces was used to monitor the evolution of tool wear in turning operations. To accelerate the progress of wear this study was carried out at an elevated cutting speed of 200 m/min (f= 0.30 mm/rev, ap = 1 mm, tool PF-4215 with cutting edge radius of 0.4 mm). The test was completed after 0.3 mm of flank wear (VB) or after 18 minutes operation time. This procedure is an approved method used by ISF of the TU Dortmund University to test Q&T steels with Rm of ~1’000 MPa.

![Graphs showing tool lifetime tests for various steels](image)

Fig. 11 Tool lifetime tests of 42CrMo4 QT, 38MnVS6, HSX-steel with sulphur (HSXZ12), HSX-steel without sulphur (HSX130HD) blue: cutting force; red: feed force; black: passive force

![Graphs showing tool lifetime tests for HSX130 and 50CrMo4Q&T](image)

Fig. 12 Tool lifetime tests of HSX130 and 50CrMo4Q&T blue: cutting force; red: feed force; black: passive force
Fig. 11 shows results of steels with \( R_m \approx 1'000 \text{ MPa} \). Bainitic steel HSX was tested as standard variant with 0.15\% S (HSX\textsuperscript{®} Z12) and without sulphur addition (HSX\textsuperscript{®} 130HD). The sizes of flank wear \( VB_{\text{max}} \) at the end of test are given in the respective diagrams.

Bainitic steel HSX in the as drawn condition (with 0.15\% S) was tempered to get a tensile strength of 1'257 MPa. In comparison with reference steel 50CrMo4Q&T (\( R_m =1'202 \text{ MPa} \)) a significant increased tool life was obtained (fig. 12).

**Outlook**

Excellent fatigue properties of TRIP assisted bainitic steels like HSX\textsuperscript{®} Z12 have been reported by customers and were confirmed by own investigations as well as by other authors [5]. However the behaviour under cyclic load depends on the amount and the condition of retained austenite. At present new steels with “mass-tailored” retained austenite are under development focussing on even more superior fatigue properties in combination with acceptable machinability.

**Acknowledgement**

The authors would like to thank

- F. Caballero, C. Garcia-Mateo from CENIM/CSIC for detailed microstructure analysis and L. Morales-Rivas from CENIM /CSIC for her excellent master thesis in this field
- Dr. J. Gibmeier of the company MaTeCon for X-ray analysis determining residual stresses and RA concentrations
- Dr. H. Klümper-Westkamp of IWT Bremen for investigating the nitriding properties of various steel compositions
- Mr. H. Hartmann and Prof. D. Biermann of ISF at the TU Dortmund University for performing the tool wear investigations and for their general support

**References**


