New Bainitic Steel for Cold Heading Applications
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Summary
A newly developed bainitic steel allows the manufacturing of high strength cold-headed parts without subsequent heat treatment. The resulting mechanical properties and technological benefits are comparable with conventionally manufactured parts using quenched and tempered steels. A strength class 8.8 or higher according to EN ISO 898 can be obtained directly from cold forging. In a joint development project between ZF Lemförder GmbH and Swiss Steel AG the first applications with this advanced steel have been completed. Using the example of ball stud manufacturing, in addition to the mechanical performance of the parts, economical and ecological advantages are seen through reduction of process steps and reduced energy consumption. The unique combination of various properties like excellent cold formability, high strength, high ductility and good weldability are resulting from the cementite-free granular bainite microstructure of this steel. This particular microstructure is obtained by a balanced combination of alloy design and production parameters during hot rolling.

Keywords: bainitic steel, granular bainite, cementite-free, cold heading, high strength, ball stud

Introduction
In the cold forging industry continuous improvement has optimised nearly every single production step to the limit. Further substantial cost reduction is only possible by reducing or eliminating entire manufacturing steps, such as heat treatment or mechanical surface processing.
Beside the continuous topic of ‘cost reduction’ there are many other challenges cold heading companies are faced with: e.g. increasing quality requirements, higher deformation degrees, more complex part geometries, lightweight construction and finally reduced energy consumption and CO₂ emission.
In the future to be able to make further progress in all of those areas and to maintain and strengthen competitiveness in a global economic environment, appropriate and enhanced steel concepts are required.

The new bainitic steel 7MnB8 (S650MC) presented in this paper enables cold forging companies and suppliers for car manufacturers to meet the increasing demands. These demands can be reached particularly regarding manufacturing costs on a large scale and extending the application limits for high strength parts without additional hardening and tempering.

Steel design, microstructure and mechanical properties
Bainitic steels, especially some low carbon steels, are now being increasingly considered as good candidates for the production of high strength cold forged parts such as bolts and fasteners, without additional heat treatment operations in the subsequent technological stages. Their mechanical properties are characterised by relatively low yield strength and appropriate strain hardening characteristics, capa-
ble of developing high strength properties after drawing and forging stages. The main idea of such steels lies in the proper control of carbon and alloying elements content to achieve the required mechanical properties. These steels are typically based on rather high content of costly elements to increase hardenability (i.a. Mo, Ni, Cr). The strength of most of these known steels is derived from the following mechanisms: solid solution strengthening, structural (grain boundary) strengthening, dislocation strengthening, second (hard) phase strengthening and strain hardening during drawing. With the exception of structural strengthening, all mentioned mechanisms result in the loss in the cold headability and the final product ductility. A diversity of bainite morphologies can be developed during hot rolling and cooling. Some of them will have a significant effect on the steel workability during cold forming and the ductility of the final product i.e. structures with larger and brittle cementite precipitations.

With regard to the design of a suitable bainitic microstructure for cold heading applications without heat treatment, it was therefore evident to consider carefully the following requirements: appropriate strengthening mechanism with minimal adverse impact on the ductility and cold formability, fine cementite-free microstructure and restricted volume fraction and fineness of minor/second phases (retained austenite/martensite). Additionally, the steel is required to have good workability in cold heading operations, to exhibit a sufficient strength level prior to shaping along with an appropriate strain hardening characteristic to develop the required properties in the ultimate product.

As a consequence the low-carbon, predominantly cementite-free granular bainite morphology was targeted in this project. This was considered as the most suitable microstructure for cold heading applications providing good cold headability and ductility (Fig. 1 and 2). Compared to lath-like upper bainite, the absence of cementite in the granular bainite makes the microstructure more resistant to void formation and failure during cold forming. Lower bainite (with a limited number of small cementite particles) would also be suitable for cold forging applications, but rather for ultra high strength cold forged parts.

An important requirement of the steel design is the low carbon content (≤ 0.1%). On one hand, decreasing carbon contents increase the bainite transformation temperature, which is essential for the formation of granular bainite (Fig. 2). On the other, it means lowering the transition temperature at a given strength and improving formability.
To increase bainitic hardenability and retard the allotriomorphic ferrite formation small amounts of boron and other bainite promoting elements (i.e. manganese, copper and nickel) are used (Fig. 3).

Finally precipitation strengthening with MX-type precipitates was used, which is quite a new idea, to maintain high strength properties in the steel wire used for cold forging. The precipitation of brittle cementite is replaced here by precipitation of finely dispersed precipitation strengthening TiC-carbides and soft second phases, which give optimum properties and formability in high strength bainitic steels.

The addition of higher titanium contents (≥ 0.06%) contributes approx. 200 MPa to the yield strength due to the precipitation of nano-particles of Ti in the bainitic ferrite. This allows to reduce the carbon content in the steel to below 0.10%, which enhances the workability in cold forming operations due to the limited amount of cementite and second phases in the structure. Another advantage of using higher titanium contents is the influence of this element on the morphology of bainite, namely, it promotes the development of granular bainite during accelerated cooling.

After balancing the alloying elements in combination with appropriate production parameters in laboratory experiments (Gleeble and dilatometer), the final chemical composition of the new steel named 7MnB8 (S650MC) could be optimised. A representative composition of this steel is shown in Table 1.

<table>
<thead>
<tr>
<th>C</th>
<th>Mn</th>
<th>Si</th>
<th>P</th>
<th>S</th>
<th>Cr</th>
<th>Ni</th>
<th>Cu+Ni</th>
<th>Mo</th>
<th>Al</th>
<th>Ti</th>
<th>V</th>
<th>B</th>
<th>N</th>
</tr>
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<tbody>
<tr>
<td>0.07</td>
<td>1.86</td>
<td>0.21</td>
<td>0.007</td>
<td>0.007</td>
<td>0.11</td>
<td>0.10</td>
<td>0.19</td>
<td>0.29</td>
<td>0.02</td>
<td>0.03</td>
<td>0.08</td>
<td>0.04</td>
<td>0.0015</td>
</tr>
</tbody>
</table>

Table 1: Typical chemical composition of the steel 7MnB8 (S650MC) in wt.-%. (The chemical composition is equivalent to steel 1.8976 (S650MC) according to EN 10149-2 for hot rolled flat products).

Fig. 4 and 5 show the most characteristic features of the steel structure after hot rolling. The steel has a cementite-free microstructure comprising a predominant phase, a minor phase and MX-precipitations (TiC) distributed within the predominant phase. The predominant phase consists of bainitic ferrite, the minor phase comprising retained austenite and optionally martensite, the relative amount of the minor phase amounting to < 20% by volume. The average grain size after conventional hot rolling is 20-30 µm (10-20 µm after thermomechanically controlled rolling, with recrystallisation or pancaked austenite without recrystallisation). The fine dispersion of the second phase in the wire rod is achieved by a proper selection of the finish rolling temperature and/or accelerated cooling after hot rolling. For product applications requiring high impact toughness at low temperatures, the refining of either the primary or the secondary microstructure is crucial [2].
The presented steel concept provides a way of achieving extremely high cold workability of the wire rod by using lean steel chemistries, and at the same time allowing the achievement of high strength properties in the final product. For example, for a wire rod with diameter 6 up to 20mm, a yield strength of 500 to 700 MPa and a tensile strength of 650 to 850 can be achieved in the as-rolled condition (Table 2). This strength is suitable for the production of parts corresponding with 8.8 to 10.9 strength class requirements (according to EN ISO 898) due to the work hardening during cold deformation without final heat treatment. Drawing and cold heading operations can increase the strength properties by approximately 300 MPa (Fig. 6).

Table 2: Mechanical properties of the steel 7MnB8 (S650MC) in the as-rolled condition (conventionally hot rolled) for diameter 6-20mm.

<table>
<thead>
<tr>
<th>Rp0.2 [MPa]</th>
<th>Rm [MPa]</th>
<th>A5 [%]</th>
<th>Z [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>520-700</td>
<td>700-870</td>
<td>17-21</td>
<td>60-71</td>
</tr>
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</table>

Besides the remarkable strength properties, the steel exhibits also very good ductility properties in the as-rolled condition, particularly a very good reduction of area of more than 60%. This is essential for cold heading operations with high deformation degrees without preliminary heat treatment. There is no substantial loss of the elongation at fracture and reduction of area during cold drawing.

Because of the low carbon content (and therefore low carbon equivalent CE) the steel 7MnB8 (S650MC) exhibits good sealing properties, which offers also new possibilities for alternative manufacturing processes.
Laboratory investigations and the production of different prototypes of cold forged parts under industrial conditions have confirmed the good cold formability of the steel.

The advantages of this new steel are shown in the next chapter in connection with the manufacturing of ball studs.

More detailed information about the development of this steel and continuative literature can be found under [3].

Manufacturing of ball studs
Ball studs (Fig. 7) and pins are important components found in ball-and-socket joints in various parts of the suspension system, e.g. transverse control arms, steering links, pin joints and stabiliser steering rods. Ball joints are spherical bearings that connect the control arms to the steering knuckles and are the pivot between the wheels and the suspension of an automobile. These components play a critical role in the reliable operation of an automobile’s steering and suspension.

Ball studs withstand static and dynamic bending loads and cyclic tension loads. Therefore the requirements regarding minimum tensile strength, fatigue resistance and toughness of ball studs are generally specified by the suppliers for car manufacturers.

The objective of the joint development project between ZF Lemförder GmbH and Swiss Steel AG was to take advantage of all the capabilities of the new bainitic steel in the manufacturing of ball studs and pins; to lower and optimise manufacturing costs, mainly by eliminating all heat treatment operations.

Fig. 8 shows the most conventional manufacturing configuration for the production of one-piece ball studs from wire rod using quenched and tempered steels. The material typically used is 41Cr4 and 42CrMo4. By using the steel grade 7MnB8 (S650MC), cost intensive process steps like drawing, annealing, quenching and tempering, straightening of longer ball studs and shot blasting steps can be eliminated. Finally advantages in logistics and flexibility provide considerable economical advantages.
Fig. 8: General process configuration for the manufacturing of one-piece ball studs: conventional using quenched and tempered steels (e.g. 41Cr4) and with the new bainitic steel 7MnB8 (S650MC).

Fig. 9 shows a selection of different one-piece cold forged ball studs made of wire rod 7MnB8 (S650MC) manufactured according to the process showed in Fig. 8.

All parts could be cold forged without issue having excellent geometrical tolerance without distortion because of the elimination of any heat treatment. Compared to quenched and tempered steels the surface quality is very good (no scaling, no points of impact and marks) and therefore the expensive mechanical surface processing can be minimised. Despite the higher strength of the new material before cold forging, tool wear was only slightly increased compared to conventional annealed quenched and tempered steels used for these applications.

To determine the mechanical-technological properties of finished ball studs, extensive tests were performed and the results were compared with the requirements and properties of parts conventionally made of quenched and tempered steels. Some results are presented in Fig. 10 to 12.
These test results demonstrate, that the mechanical-technological properties of the non heat treated ball studs meet the specified requirements and are comparable with conventionally produced components made of quenched and tempered steels (i.e. 41Cr4).

**Conclusion**

As a result of the well designed microstructure and the resulting excellent combination of mechanical-technological properties, the new bainitic steel 7MnB8 (S650MC) is optimally qualified for cold forging of high strength parts without heat treatment. This offers new possibilities to the cold forging industry: e.g. substantial reduction of process chains and therefore process cost, implementation of new or modified manufacturing processes and the realisation of new applications. The properties of balls studs made of the new bainitic steel without heat treatment operations are similar in comparison with parts made of quenched and tempered steels and meet all the requirements.
The main **advantages** of this new bainitic steel regarding cold forging applications in general are listed below:

**Cost saving options** due to:
- Elimination of all heat treatment steps
- Alternative and more cost-effective processes (i.e. welding operations)
- Elimination of straightening of long parts
- Reduction of mechanical surface processing
- Reduction of inspection effort
- Reduction of logistics cost
- Improved flexibility

**Improved ecological benefits** due to:
- Reduction of energy consumption and CO$_2$ emission

**References**

