

Guest editorial of “Application of high strength steels in lightweight commercial vehicles”

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H. Mohrbacher

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New and increasingly sharp laws for the reduction of emissions from commercial vehicles entered into force in the European Union since 1993 with the aim of substantially reducing pollutants and emissions from trucks and buses. Thereby the maximum levels for the emission of particulate matter (basically soot particles) as well as oxides of nitrogen (NO_x) have been subsequently lowered. To comply with these demands, commercial vehicle producers had to introduce new emission reducing technologies of which exhaust-gas recirculation (EGR), selective catalytic reduction (SCR) and diesel particle filters (DPF/ CRT) are vital. However, the implementation of such technologies in a commercial vehicle causes a weight increase that can be estimated to reach 300 kg. Practically this means that for instance the capacity of a bus would have to be reduced by four passenger seats unless the extra vehicle weight is reduced in other areas of the vehicle.

Unlike in passenger cars, maximum CO_2 emissions are not yet being specified by European regulations for commercial vehicles (see Fig. 1). CO_2 emissions (of course all other emissions) are directly proportional to the fuel consumption of the vehicle, which in turn can be reduced by higher efficiency in the powertrain, lower vehicle weight and improved aerodynamics.

However, what actually counts beyond the absolute emissions and efficiency of a commercial vehicle is its relative performance per ton of transported cargo. A lighter vehicle simply allows transporting more cargo respecting a given total admitted vehicle weight on the road. Accordingly, the emission per ton of transported cargo becomes less.

Improved design, better-performing materials and innovative manufacturing technology each by itself enable light weighting of vehicle structures and efficiency gains in the powertrain. However, the optimum benefit can only be obtained by a holistic approach involving all three approaches in a coordinated way. China Automotive Lightweight Association (CALA) was installed in 2008 to work out strategies of weight reduction in the automotive sector.

In November 2014 CITIC Metals and Companhia Brasileira de Metalurgia e Mineração (CBMM) organized a seminar in Beijing focusing on the “Application of high strength steels in lightweight commercial vehicles”. Around 90 experts from organization delegated by commercial vehicle producers, CALA, China Iron and Steel Research Institute (CISRI), steelmakers and supply companies participated to identify the opportunities and needs for producing lighter and more fuel-efficient trucks in China. Two facts emphasize the urgency of these activities:

- (i) About 20% of the Chinese vehicle fleet is commercial vehicles yet combusting more than 50% of the total fuel consumption.
- (ii) Chinese domestic trucks consume in average 20% more fuel as compared to European ones.

Since China has powerful steel industry equipped with most modern mills, it is the most obvious to explore the possibilities of modern high performance steels for achieving a better fuel efficiency of commercial vehicles. This does of course not exclude that other materials could contribute to achieving this goal as well.

In the subsequent contributions the most important information disseminated during the seminar is being reproduced and summarized. Thereby the following main topics are being addressed:

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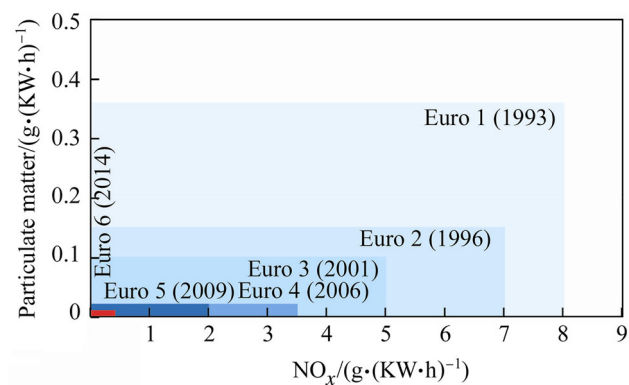


Fig. 1 Maximum limits for oxides of nitrogen and particulate matter emissions according to European emission standards level 1–6

- Innovative manufacturing technology enabling light weighting with steel in commercial vehicles
- Light weighting opportunities and material choice for commercial vehicle frame structure
- Application potential of high performance steels for weight reduction and efficiency increases in commercial vehicles
- Sustainable development of China's commercial vehicles

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Innovative manufacturing technology enabling light weighting with steel in commercial vehicles

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Abstract Improved manufacturing technology is often needed when working with high strength steel. In this respect manufacturing technology has to adapt to the altered (and typically reduced) formability and weldability of modern high strength steel. However, this is a rather passive approach from a manufacturing point of view. An indeed much more powerful approach is to generate synergies between innovative manufacturing technology, design and material enabling additional weight savings and efficiency gains. Laser-based material processing, in particular laser welding, offers a wide range of opportunities in this sense. Furthermore, hot stamping and roll forming open up new possibilities for advanced manufacturing of commercial vehicle components. Applications and examples of these technologies will be given in terms of producing innovative semi-products as well as final components.

Keywords Commercial vehicles · Light weighting · High strength steel · Roll forming · Press forming · Hot stamping · Tailor-welded blanks · Tailor-welded coils

1 Weight reduction trends at Chinese truck producers

China has installed a “National Program for Energy Conservation in Vehicles” in 2012. Accordingly, vehicles must

become more fuel-efficient, and resources needed for vehicle production should be saved. Commercial vehicles are lacking the Western standards in this respect. It is estimated that Chinese commercial vehicles consume 20% more fuel than their European or Japanese counterparts. Strategies for weight reduction have been plotted using material upgrading and design changes as the main approach to close that gap. This approach naturally directly affects manufacturing technology as upgraded materials are often more difficult to process, and this will also decide whether the desired design can be realized. Another key consideration in this respect is cost. Widespread use of low-density materials such as aluminum, magnesium or plastics has been proven to provide significant weight reduction opportunities. However, these materials are expensive; hence it conflicts with the demand for low cost solutions considering the rather moderate sales price for trucks on the Chinese market. Higher strength steel was found to show the best performance versus the cost balance for many major truck components allowing weight reduction to be either cost neutral or even cheaper as compared to the traditional solution.

Over recent years the First Automotive Works (FAW) replaced conventional 16Mn steel by high strength grade 590L (the minimum yield strength = 520 MPa) in longitudinal beams of newly designed truck frames (see Fig. 1), reducing their weight by around 150 kg. Simultaneously the fatigue resistance of such beams increased over 40%. Dongfeng adopted high strength steel grade 700L (the minimum yield strength = 670 MPa) in the frame of 14 different truck models, achieving weight reductions from 188 kg to 125 kg depending on the frame size (see Fig. 2). Similarly, FAW achieved 29% weight reduction in longitudinal beams using grade 700L.

Meanwhile the yield strength of frame steels has progressed to 700 MPa in some models enabling further

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Fig. 1 FAW truck frame comprising longitudinal beams made from grade 590L steel



Fig. 2 Dongfeng truck frame using 700L high strength steel

weight reduction. Application of this steel grade in a Dongfeng 6×4 towing truck (see Fig. 3) resulted in 220 kg weight saving. The combined approach of an integrated design of main and auxiliary frame together with the application of 700 MPa yield strength steel (grade 750L) in an 8×4 dump truck (see Fig. 4) allowed an impressive weight reduction of approximately 800 kg.

While the introduction of steel grades with 700 MPa yield strength in longitudinal beams has become a priority for Chinese truck producers, the application of steels having strength beyond that level is already on the horizon for even further weight reduction. Grade 960QC with the minimum yield strength of 960 MPa can be produced by direct quenching after hot rolling. The development of this grade is in progress in some Chinese steel mills. Alternatively, trials to achieve this ultra-high strength level have been done at truck producers by heat treatment of beams. In principle, application of this steel grade has another weight reduction potential of up to 25%.

The use of steel grades Q235 and Q345 has been the standard for the construction of trailer chassis in China before 2009. The gages of such grades could be quite heavy as a result of common overloading practice and road conditions. Since 2009 higher strength steels are being used to significantly reduce the beam gages and thus the weight. Longitudinal beams in trailers often use I-shape typically with variable cross sections. Therefore these beams are usually welded incorporating different gages in the web and flanges. Cross members connecting the longitudinal



Fig. 3 Dongfeng 6×4 towing truck



Fig. 4 Dongfeng 8×4 dump truck

beams use C- or I-shape of typically constant cross section, which can be produced by roll forming or net shape hot rolling. The chassis of a typical kingpin design semi-trailer (see Fig. 5) consists of around 3 200 kg steel when using conventional Q235-Q345 grades. By upgrading the steel to grades 590L and 700L weight reduction of over 20% is possible. For instance, an I-beam in Q345 of dimension $150\text{mm} \times 465\text{mm}$ with flange and web thicknesses of 12 mm and 5 mm, respectively, has a specific weight of 47 kg/m. An I-beam in grade 700L of the same dimension achieves approximately the same bending and shear capacity with flange and web thicknesses reduced to 8 mm and 4 mm, respectively. The specific weight of the

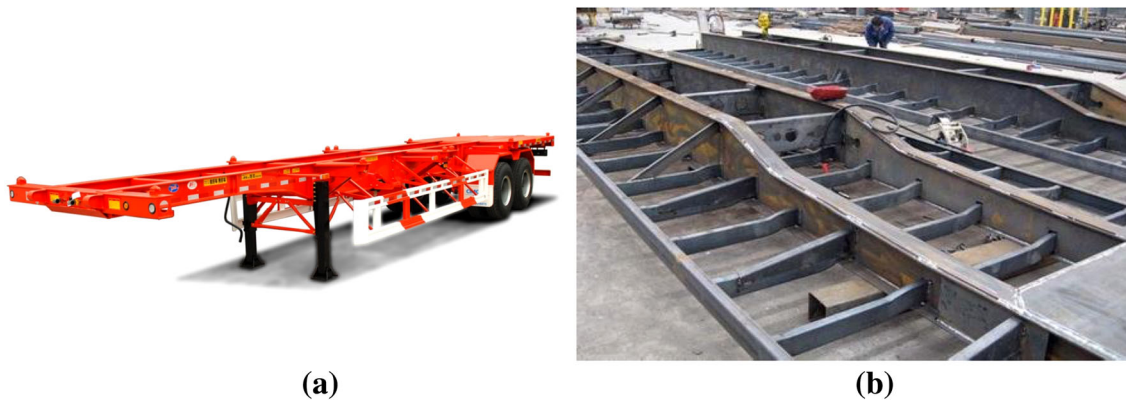


Fig. 5 Kingpin-type trailer chassis (CIMC (a)) and assembly process of longitudinal and cross beams (Shougang (b))

upgraded beam is only 34 kg/m, i.e., 27% less than the conventional reference.

The cabin of commercial vehicles is mainly constructed from press stamped steel sheet. Traditionally mild steel (tensile strength up to 270 MPa) with good press formability was used in this area. Gradually, steel with increased strength has been introduced for some cabin parts over the last 15 years. The respective steel grades are mostly higher strength interstitial free (IF) and bake hardening (BH) steel grades, which still offer very good cold formability. Due to the increased strength (340–440 MPa), sheet thickness could be reduced, resulting in a small weight reduction. FAW succeeded in that way reducing the weight of its CA1092 truck cabin by 21 kg corresponding to less than 5% of the total cabin weight. Meanwhile dual-phase (DP) steels of 500–650 MPa tensile strength have been introduced in specific parts where efficient crash energy absorption is important (see Fig. 6). These are longitudinal beams in the floor, roof and rocker area.

The extensive use of high strength steel grades and specific manufacturing technologies in the body-in-white (BIW) of passenger cars have demonstrated that weight reductions of 20% to over 30% can be achieved. Such a far going approach has not yet been applied to truck cabins although it is possible in principle.

Wheels significantly contribute to the mass of a commercial vehicle and are a particularly interesting area for reducing weight. The weight of steel wheels in mainstream trucks and trailers typically ranges between 40 kg and 50 kg. Since wheels represent rotating masses, less weight and accordingly lower inertia can reduce fuel consumption by up to 2.5%. Furthermore, the reduced unsprung mass of a weight-reduced wheel lowers wear of the suspension and shock damper. Analysis by finite element method (FEM) calculations and field trials (see Fig. 7) has indicated that replacing conventional wheel steel by higher strength grades can reduce the wheel weight by up to 30%. Replacement of twin wheels by a single wheel with extra-wide tire (see Fig. 8) enables additional weight reduction of around 20%.

For all application areas discussed above, the upgrading of material has an important impact on the manufacturing processes applied in the fabrication of vehicle components. The concerned principal processes are cutting, forming and welding. Accordingly material properties such as hardness, formability and weldability have to be considered and need eventually to be optimized. The most decisive one in that respect is the microstructure and chemical composition of the steel.

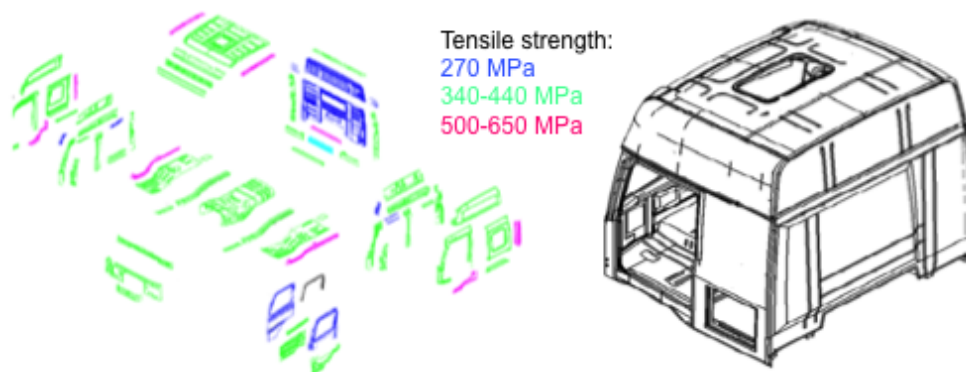


Fig. 6 Application of higher strength steel grades in press stamped components for the truck cabin

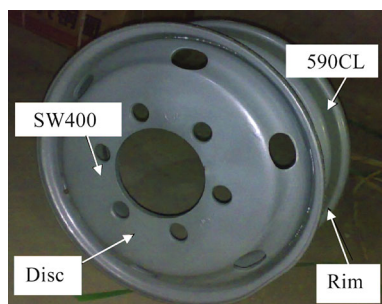


Fig. 7 Truck wheel using high strength steel for rim and disc



Fig. 8 Replacement of a 22.5×9.00 twin wheel (82 kg) by 22.5×17.00 single wheel (64 kg)

2 Manufacturing trends and material considerations for chassis components and profiles

The traditional forming method of producing straight beams and profiles has been press brake bending, requiring the use of expensive tools that do not offer flexibility with regard to part design variations. Press brake bending also has limitations when using steel of increased strength. Alternatively the use of welded beams has been established for non-straight and/or variable cross-section beams. Nowadays long chassis beams for trucks are primarily produced on flexible and automatic roll forming lines (see Fig. 9). This technology was introduced in the early 1990s [1]. The lines are equipped with a range of NC adjustments and changeover functions enabling transition from one profile to another to be completed in a short set-up time of only a few minutes. The profile thickness can range from 4 mm to 12 mm at roll forming speeds up to 24 m/min. Roll formed truck chassis side beams with constant cross sectional shape have gradually replaced beams produced by the traditional press-based method.

The restriction of producing profiles with a constant cross sectional shape in longitudinal direction has been overcome by the development of the so-called “flexible” roll forming process [2]. Machines have been designed and built allowing roll forming of variable section (see Fig. 10).

So far most of these products have been manufactured through large presses and welding centers, which bend and weld pieces of appropriate shapes in order to construct the beam from individual sub-sections. In addition to the considerable manpower and space needed for production, the pieces obtained from the pressing and welding operations reveal distortions and deformations, which consequently must be corrected by straightening operations. The possibility of producing such special beams through the automatic and continuous roll forming method thus represents a serious advantage in terms of flexibility and personnel employed, while quality is improved and the cost of the final product is being reduced. Straightening that is necessary in a welded beam can be avoided by flexible roll forming. Furthermore, residual stresses that add to the applied load stress are being reduced. Naturally a machine of such mechanical complexity requires an electrical and electronic control system of the highest level since it can involve more than 100 dynamic axes, which are constantly changing position during the roll forming operation. Additionally more than 40 fixed axes are positioned according to the profile to be produced and will be constantly maintained in position during the process.

For chassis components of trucks and trailers hot rolled steel is used with gages of up to 20 mm. The use of high strength steel for chassis components has started in the 1980s. Today the application of extra high strength steels is state of the art. For instance European truck manufacturers nowadays regularly use S700MC (the minimum yield strength is 700 MPa) for longitudinal beams in frames. In the last years, truck manufacturers in China have also applied this approach initially using imported S700MC steel sheet. Due to the increasing domestic demand several Chinese steel mills have established production of this steel grade replacing imports. The development of these steel grades incorporated manufacturing aspects such as cutting/drilling, forming and welding. In the following the property profile for such steel is derived from a manufacturing point of view:

- (i) Good bendability is a key property for roll forming or press brake bending. The use of extra and ultra high strength steels for producing open-ended profiles causes increased dimensional deviations in the finished part. These are due to elastic spring back as a consequence of residual stresses present in the formed material. That effect increases with the increase in yield strength of the steel. Shape deviation caused by spring back can be compensated for by either introducing geometrical constraints (stiffeners) or a defined amount of over-bending. The over-bending approach, however, demands narrow statistical scatter of yield



Fig. 9 Production of longitudinal beams for truck frame by roll forming

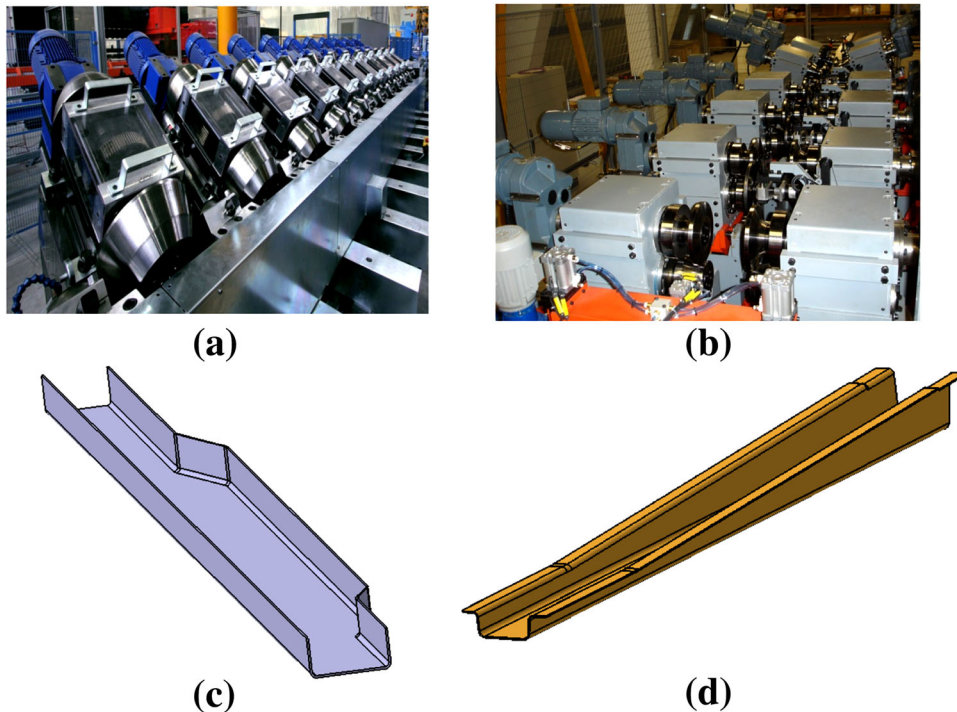


Fig. 10 Equipment for 3D roll forming at Gestamp and possible part shapes with geometrical variation in width (a, b) and depth (c, d) directions

strength to be reliable. This not only concerns the scatter from coil to coil but also scatters within a coil, i.e., along rolling and transverse directions.

- (ii) Shearing, punching and other methods of cutting have a negative effect on subsequent flanging (hole expansion) operations and on fatigue properties during service due to the formation of microcracks in the cut edge. Under sufficiently high stress the induced microcracks will propagate leading to splitting during forming or a reduced fatigue life of the final component.
- (iii) The presence of hard phases in the steel matrix causes increased wear on cutting or drilling tools. Experience indicated that laser- and plasma cutting methods are superior methods for achieving

damage-free edges. In these methods wear is not an issue. However, the heat influence can modify the microstructure of the material at the edge. Excessive hardening of the edge should be avoided.

- (iv) Metal active gas (MAG) welding and manual metal arc welding are typical processes for assembly welding of frame parts. Submerged arc welding is rather used to compose heavy-gaged I-beams. The microstructure in the heat-affected zone (HAZ) varies depending on chemical composition of the steel and heat input during welding. Strength and impact toughness change corresponding to the microstructural change but should not be below the specifications for the base material.

In China recent development of steel grades for truck frames with 600 MPa yield strength and higher has been focusing on chemistries with low carbon content and Nb-Ti dual microalloying. With this concept either polygonal ferritic or bainitic microstructure with precipitation strengthening can be adjusted depending on the run-out table conditions in the hot-strip mill. The presence of pearlite or other hard phases in the microstructure is preferably avoided as these have a negative impact on the bendability. Furthermore, such hard particles also lead to edge damage after mechanical cutting and cause increased wear on cutting tools. Due to fine grain size and low carbon content these steels intrinsically feature high toughness. For 700 MPa yield strength most concepts are based on 0.06%C-1.8%Mn-0.06%Nb-Ti-Mo alloying. This concept exhibits a remarkable robustness against temperature variations on the run-out table of the hot-strip mill (see Fig. 11). At higher coiling temperature fine-grained polygonal ferrite with precipitation strengthening is obtained while for lower coiling temperature bainitic microstructure prevails with less precipitation strengthening [3]. Both types end up with very similar yield and tensile strength. Narrow scattering of strength evidences this during production campaigns (see Fig. 12). The ferritic microstructure usually shows higher elongation while the bainitic microstructure offers better toughness [4]. Either microstructure is excellently suited for bending operations or exhibits smooth cutting edges (see Fig. 13) [5]. Production material of several Chinese steelmakers using this alloy concept reached Charpy toughness values of over 100 J at -20°C .

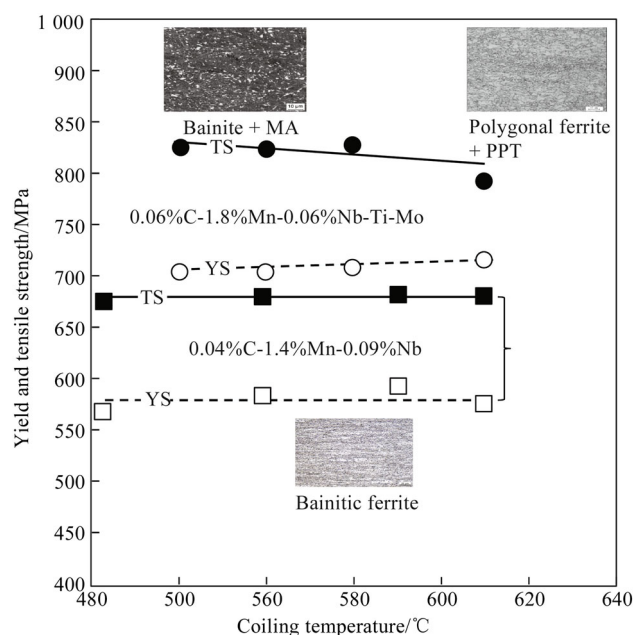


Fig. 11 Robust low-carbon concepts of extra-high strength steels and influence of coiling temperature on strength variation

The strength of MAG weld seams in these steels depends on the heat input and the type of welding wire used [6, 7]. To obtain the minimum specified tensile strength for the 700 MPa grade in a transverse tensile test, the heat input is limited to approximately 11 kJ/cm. Using matching weld wires such as GHS-70 or OK Autrod 13.13 leads to rupture in the weld metal. When using overmatching wires such as ER-80 or OK Autrod 13.31 rupture occurs in the base metal. Due to the low carbon content (0.06%) used in these steels, peak hardness in the HAZ remains below 350HV even at the lowest heat input. Consequently there is no risk of cold cracking.

Current developments by Chinese steelmakers aim at producing hot-strip with yield strength above 900 MPa. This strength level was so far only available as quenched and tempered plate material. The intended processing route for hot-rolled strip is based on direct quenching (DQ) from the rolling heat avoiding the cost of additional off-line heat treatment. To achieve strength above 900 MPa by DQ rolling the chemistry of the steel has to be enriched as compared to the 700 MPa grade. Carbon is typically in the

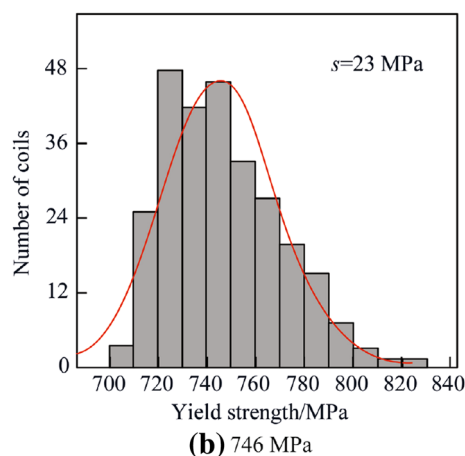
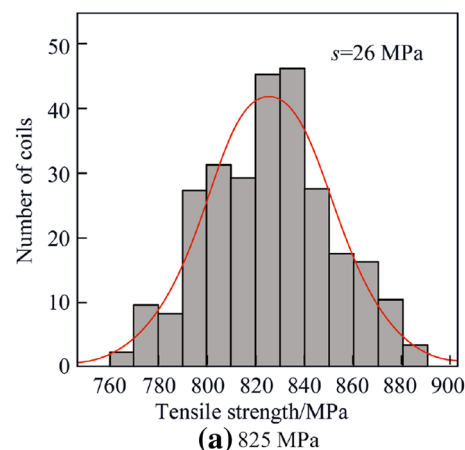


Fig. 12 Narrow strength variation in extra-high strength grade SQ700MCD produced by Shougang

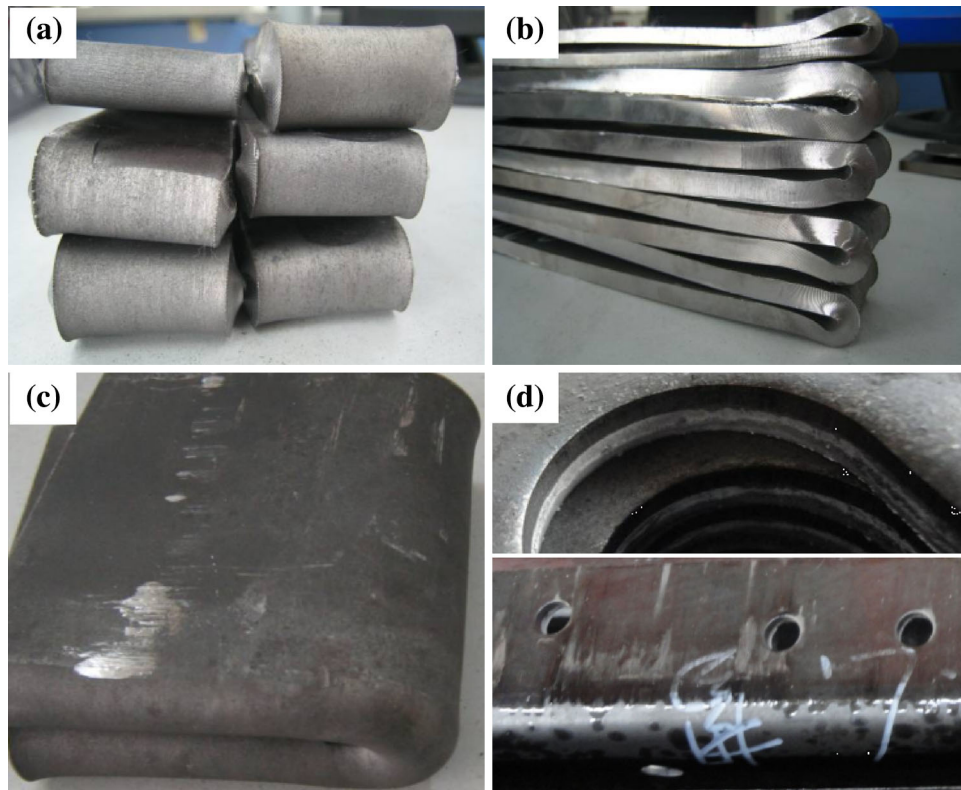


Fig. 13 Bendability of hot rolled strip with 700 MPa yield strength (courtesy Ma steel)

range of 0.08%–0.10%. Niobium additions of around 0.03% appear to be the optimum for this steel grade. Alloying of boron or molybdenum either alone or in combination provides sufficient through-hardenability. Other microalloying elements can be added for precipitation strengthening in case a tempering condition after quenching is being performed. The microstructure of this steel is either martensite or tempered martensite, which exhibits a marked anisotropy between rolling and transverse direction (see Fig. 14). Trials have revealed that bendability along the rolling direction is usually good whereas severe cracking can occur under bending along the transverse direction. The latter effect is observed when undesirable microstructural phases form as a consequence of very high total rolling reduction and low finish-rolling temperature [8]. The good bendability parallel to the rolling direction makes such steel instantly suitable for roll forming.

The weldability of DQ steel grades with the minimum yield strength 900 MPa is not as good as that of 700 MPa grades. It is due to the heat sensitive base microstructure of that steel as well as its higher carbon equivalent and thus better hardenability. Considering MAG welding as a reference technique, the maximum heat input is limited to 12 kJ/cm. The high heat input causes pronounced softening in the HAZ. On the contrary, heat input below 10 kJ/cm

results in excessive hardness peaks, making the HAZ sensitive for cold cracking.

3 Lightweight solutions for truck cabins

Components for truck cabins are mainly produced from cold-rolled steel sheet. Due to the rapid development of light weighting of passenger cars in China over recent years, Chinese steelmakers are nowadays ready to supply the full range of steel grades up to strength levels above 1 000 MPa. Truck cabins have not yet adapted such an intensive use of ultra-high strength steels as compared to car bodies. As mentioned before, the use of medium high strength steel with yield strength of around 350 MPa has been widely established. Dual-phase steel with tensile strength of 590 MPa is being used in selected components for crash energy absorption. Further weight savings and optimization of crash resistance are possible by using DP steel with 780 MPa tensile strength as well as complex phase (CP) and hot stamping steels. Compared to car bodies, the size of components for truck cabins is usually much bigger. The corresponding larger size of sheet blanks required for manufacturing truck cabin components sometimes conflicts with the available steel coil

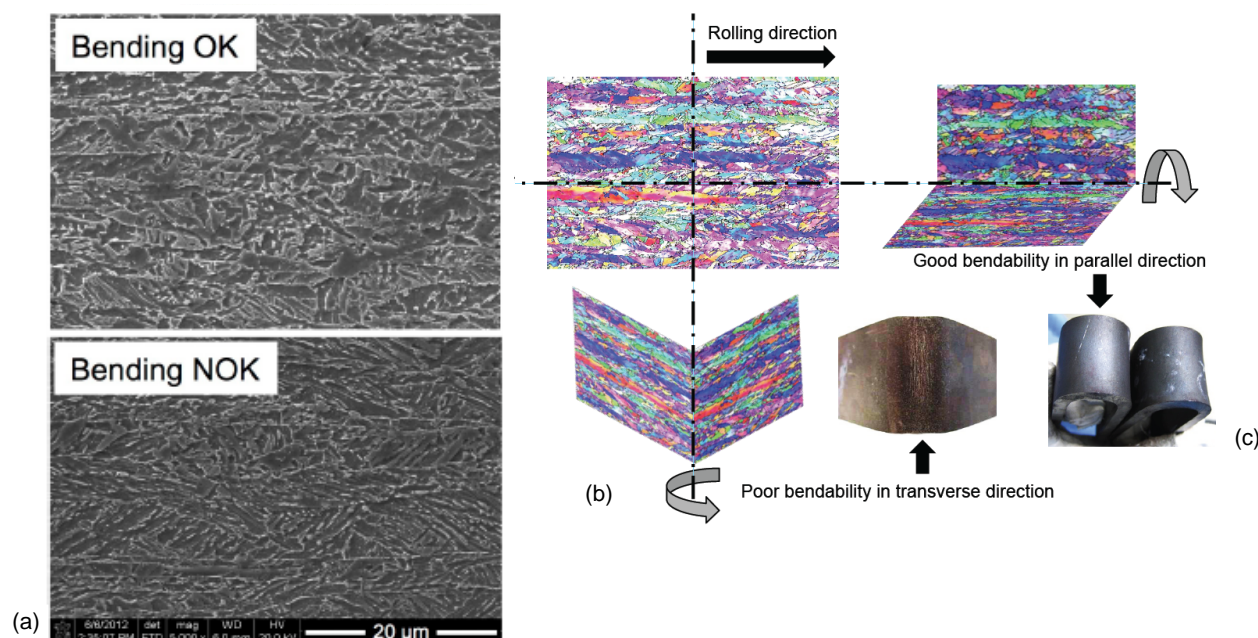


Fig. 14 Microstructural features of DQ steel by SEM (a), EBSD (b) and influence on bendability (c)

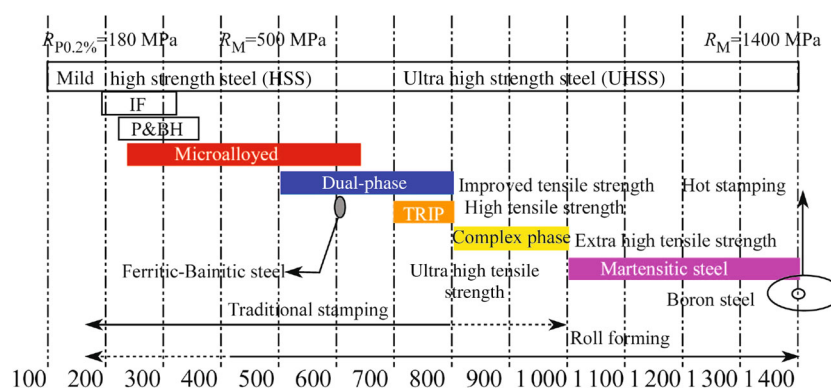


Fig. 15 Automotive steel grades and typical forming techniques as a function of strength

dimensions, especially for very high strength steels. In other cases, the available press force for stamping such ultra-high strength steels might be insufficient.

Advanced manufacturing technology can assist the application of ultra-high strength steels in truck cabins at competitive cost and also allows realizing additional weight saving potential (see Fig. 15). The usage of ultra-high strength steels such as DP780, DP980 or DP1180 for reinforcements in the cabin structure became possible by the roll forming process. Alternatively cabin rails recently were specified as press hardened steel with the main intent of improving stiffness and part weight. Better crash behavior appears as a secondary effect. Furthermore, laser welding and laser welded semi-products play a key role in this respect.

Laser welded blank technology was originally installed in Germany in 1985 to provide oversize blanks for car components that could not be supplied from coil dimensions available in the market [9]. The characteristic of laser welding is a very narrow weld that exposes good formability and does not cause corrosion problems. Production equipment has been developed over three decades allowing efficient welding of such blanks with the highest quality standards [10]. Today China disposes over a large domestic supply base for laser-welded blanks. With regard to oversize blanks, the existing laser welding equipment can generate all dimensions needed for large size components such as floor panels, roof panels, back panels or side panels. Since the sub-blanks are welded in butt configuration there is no material overlap. Neither does the weld comprise over-

thickness or under-cut. Therefore a laser butt weld could be also used in the visible area of commercial vehicles. Combination of different sheet gages and steel grades has led to the so-called “tailor welded blank” (TWB) technology. Thus TWB technology enables additional weight savings and production efficiencies. By configuring originally individual components as sub-areas of a TWB, one or more stamping die sets can be eliminated together with the respective press occupation, assembly operations and part logistics. In addition avoiding large areas of trim scrap increases the material utilization.

A TWB design example of a truck cabin door is shown in Fig. 16. In a conventional design, the door inner panel and the window frame are stamped as single blanks. Thereby the gage required in the window frame area is the largest due to stiffness considerations. Hence the door inner panel area carries a larger thickness and thus higher weight than actually needed in that area. The single blank also comprises a large cutout area lost as trim scrap. For the hinge area an additional reinforcement part needs to be stamped and then spot-welded into the door inner blank. A typical TWB design solution combines the individual blanks with optimized thickness to an integrated component. Optimum nesting of sub-blanks during the cutting operation results in very high material utilization. Another TWB design example for the main floor assembly is shown in Fig. 17. The conventional design consists of 9 individual stampings. The center-floor is assembled with the left and right floor-sides. The overlaps need to be sealed with an adhesive. Three longitudinal reinforcement inserts are spot-welded into each floor-side. By TWB technology these 9 stampings can be reduced to 3 stampings (floor, LH and RH longitudinals). The longitudinals are spot-welded under the floor. The continuous laser weld seams make sealing obsolete and result in an entirely stiffer construction.

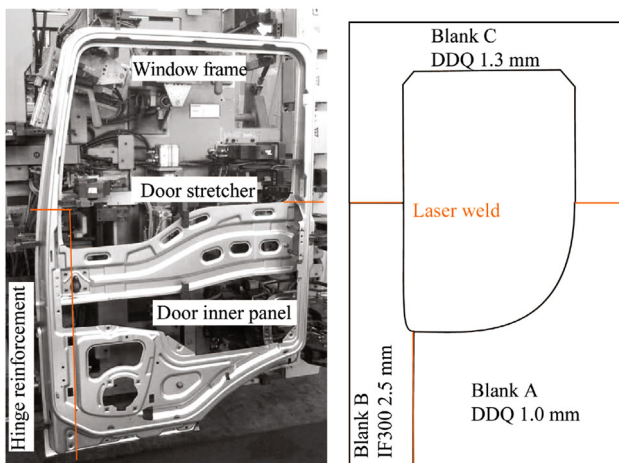


Fig. 16 Tailor-welded blank designed for a truck cabin door optimizing function, weight and material utilization

Truck cabins as well as inner frame structure of busses offer good opportunities for profile-intensive design (see Fig. 18). Initial and part-specific investments for roll forming are more economical than those for press stamping (see Fig. 19). The cost advantage of roll forming over press stamping increases with the length of the part to be produced. Roll forming is also less demanding the material in terms of formability. Consequently stronger steels can be processed (see Fig. 15). The steel needs to have good bendability, however, and this again is related to microstructural details as will be discussed later. Roll forming lines are available in various sizes and variable modular configurations (see Fig. 20). The spectrum of products ranges from simple U-shaped profiles to complex geometries as shown in Fig. 18. It is also possible to close the profile to a shaped tube by integrating a laser-welding unit behind the roll forming station. An in-line stamping unit ahead of the roll forming station allows performing cutouts.

Remarkable potential lies in the combination of roll forming with tailor welded coil technology. In the latter, two or more steel coils are de-coiled and laser-welded against each other along the strip edge before being re-coiled (see Fig. 21) [10]. In this way different gages and steel grades can be combined to a composite coil. Roll forming a tailored coil results in a profile that can have variable gages optimizing structural requirements and component weight as exemplarily indicated in Fig. 21. With this option weight saving potential of up to 40% appears feasible for roll formed profiles.

With regard to bendability of cold-rolled steel with ultra-high strength, microstructural details are an important

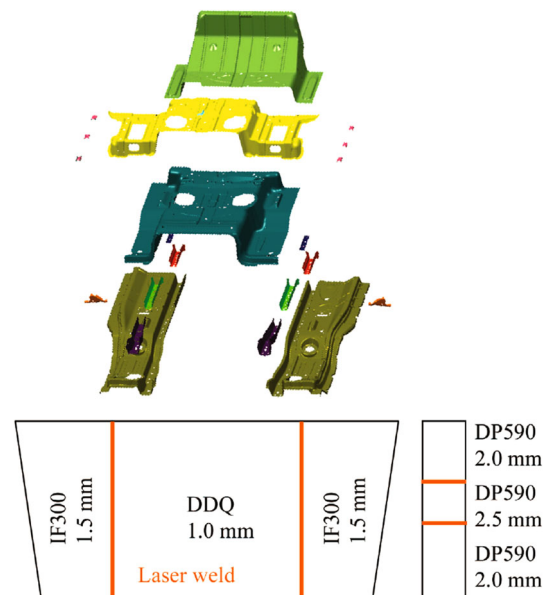


Fig. 17 Tailor-welded blank designed for a truck cabin floor assembly with high degree of part reduction

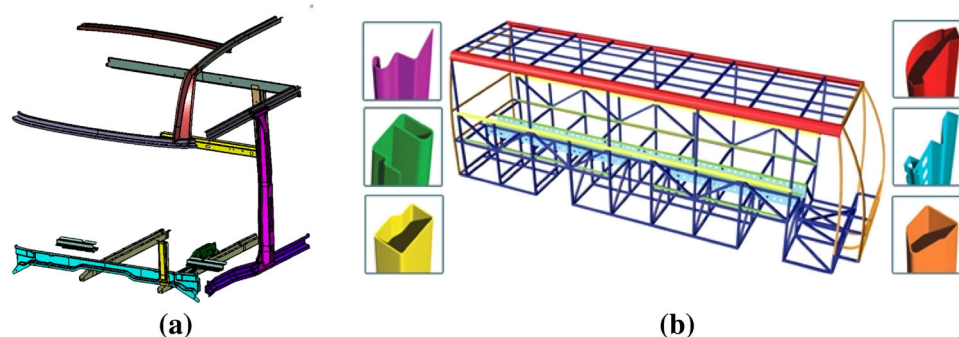


Fig. 18 Profile-intensive designs for truck cabin (a) and bus body using open and closed profiles (b)

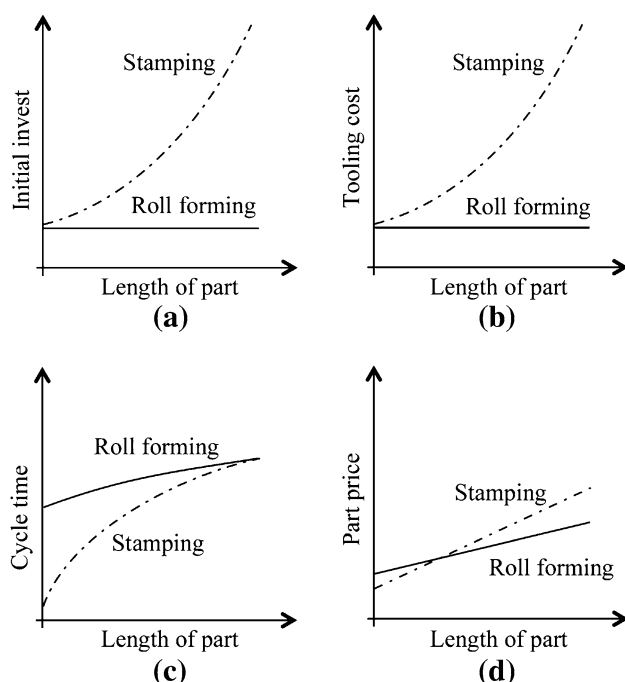
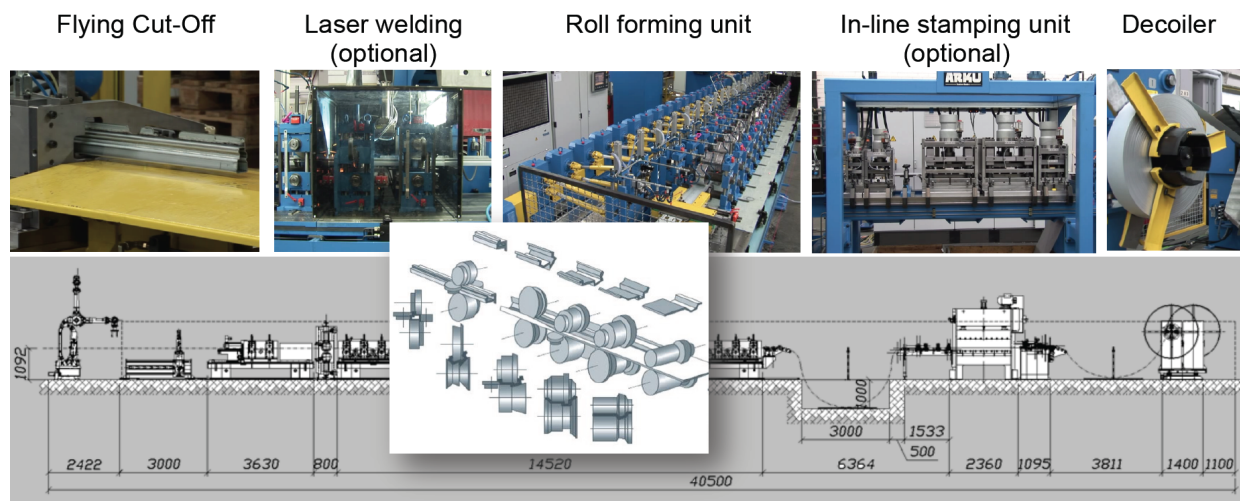


Fig. 19 Principle economical comparison between roll forming and press stamping

criterion. It has often been experienced that DP steel is sensitive to corner cracking during die bending or roll profiling. This is related to the inherently inhomogeneous microstructure of DP steel consisting of hard martensite islands dispersed in a soft ferrite matrix. Strain concentration at the hard-to-soft interface first leads to delamination and finally to crack especially when martensite islands are clustered and their morphology is coarse [11, 12]. Microstructural refinement by adding a small amount of niobium to the steel has been proven to significantly reduce that problem (see Fig. 22). The metallurgical technology of optimizing bendability of DP steel is already being practiced by Chinese steelmakers. Accordingly the critical bending radius can be increased from 30% to 50% compare to non-refined DP steel

(see Fig. 22). By such optimization the use of DP780 or DP980 roll profiles became possible for instance as support beams for bus seats. Using DP980 for roll formed bus seat support beams (see Fig. 23) allows reducing 1 kg of weight per seat unit as compared to formerly used HSLA. The use of tailored coil material for these profiles could further reduce the weight of these beams by 20%. In the same ratio the cost of steel would be lowered as well compensating the cost of producing the tailored coil.

In recent years, press-hardening (hot stamping) technology has developed very quickly as a key weight reducing technology in car bodies. The sheet is heated to austenite temperature (around 950 °C) by a tunnel furnace in front of the stamping line. The hot sheet is transferred to the die and is then immediately stamped into shape. During stamping the material is soft (austenitic) and very well formable. When the usually water-cooled die is closed, intimate contact with the sheet results in rapid cooling, transforming the soft austenitic microstructure into martensite, which is very strong. The standard steel grade used for hot stamping is 22MnB5 providing a tensile strength of at least 1 500 MPa after hardening. Press hardening technology allows to severely reduce sheet gage of a component or even to omit reinforcement parts that were necessary when working with softer steels. As such, weight reductions of around 30% are possible with hot stamped components. The application of hot stamped components is the most appropriate in areas where high impact load is expected during a crash and where little or no plastic deformation is wanted. In a truck cabin these components are typically A-pillar, roof header, bumper beam or front crossbeam. Since these components are loaded by impact in a crash situation, the material should have sufficient toughness avoiding fracture with low energy dissipation. Martensite, although often being perceived as being brittle, in the case of 22MnB5 is providing sufficient toughness with ductile fracture at ambient temperature to sustain crash impact. At lower temperature however, this behavior can change by transition to brittle fracture combined with



Note: Length indications in millimeters

Fig. 20 Configuration of a medium-sized roll-forming line and principle of the profiling process

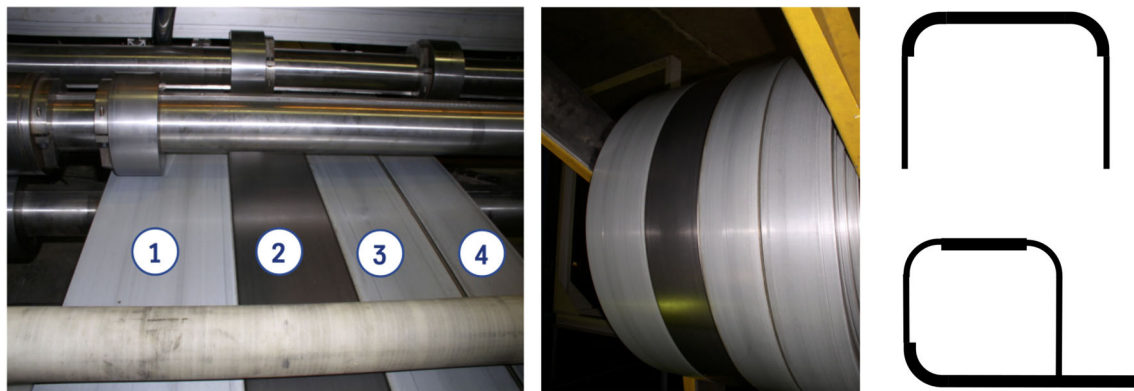


Fig. 21 Example of tailor-welded coil consisting of 4 slit coils and examples of possible multi-gage profiles by roll forming

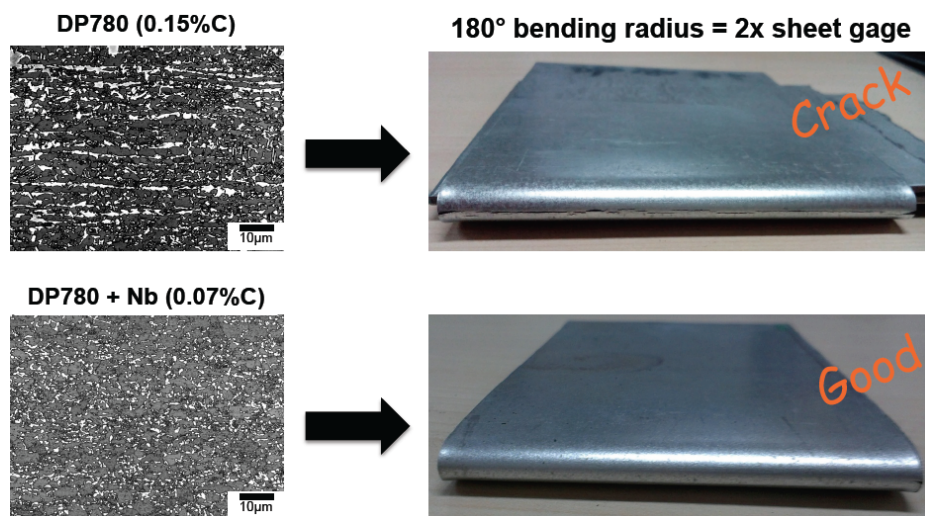


Fig. 22 Microstructural optimization of DP780 steel (Nb microalloying and lowering of carbon content) and resulting improvement of bendability (courtesy Shougang)

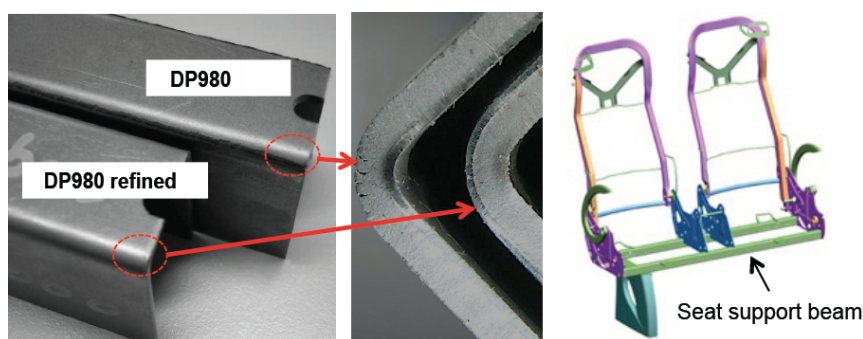


Fig. 23 Roll formed profiles of DP980 steel and appearance of corner cracking with non-optimized microstructure; application example for bus seat support beams

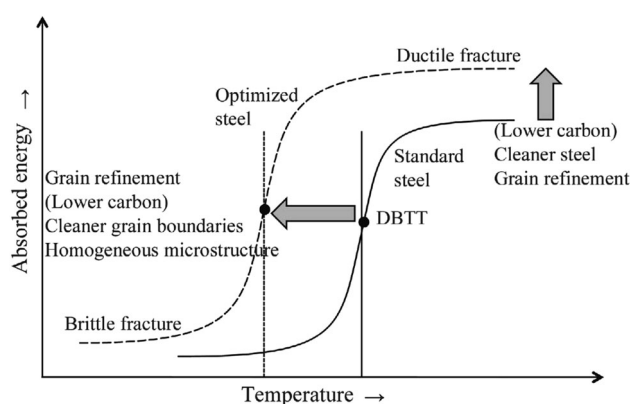


Fig. 24 Metallurgical means of improving toughness behavior in press hardening steel

much-reduced toughness. The temperature at which this transition occurs should be below the lowest operating temperature of the vehicle to ensure safe behavior of the component under all possible circumstances. The actual ductile-to-brittle temperature of martensite is decisively influenced by the effective grain size in the martensite microstructure (see Fig. 24) [13]. Finer effective grain size reduces the transition temperature, which is favorable [14]. Refining the original grain size in the non-hardened steel strip by the steelmaker can firstly optimize the effective grain size of such press hardening steel. In addition, unwanted grain coarsening during the heating process in the press hardening line has to be avoided. Intensive research has demonstrated that an addition of 0.05% niobium to press hardening steel can effectively achieve the initial grain refinement and safeguard unwanted grain coarsening during press hardening (see Fig. 25) [13].

4 Innovative manufacturing concepts for wheels

The manufacturing of steel wheels involves numerous cutting, forming and welding operations (see Fig. 26). The truck

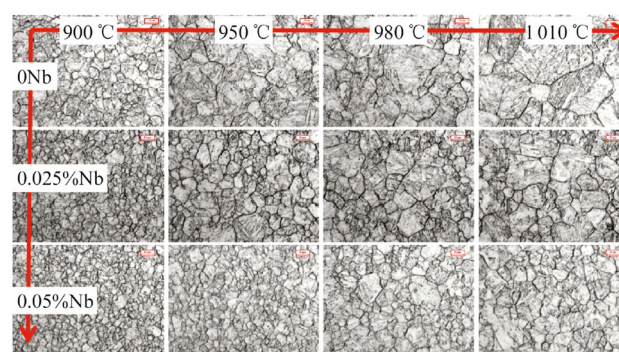


Fig. 25 Influence of niobium microalloying on effective grain size for different reheating temperatures (alloy base: 22MnB5)

wheel disc is made from rather thick gage for stability reasons. At the outer area the gage is often being reduced by spin forming to lower weight. Subsequently the disc is drawn to shape in several steps before cutting openings. For producing the rim a flat steel strip is rolled to a ring, which is then closed by flash butt welding. The area that is clamped into the welding machine needs to be flattened before welding and re-rounded after welding. The local over-thickness at the weld caused by upsetting has to be removed and smoothened. Finally the disc is joined with the rim by press fitting. Welding is executed under 45° using MAG or submerged arc welding (SAW), depending on material thickness. Thereafter a straightening and calibration procedure removes heat distortions originating from this assembly welding process. The steel grades used for wheel making have to comply with these forming and welding operations. Steel for producing the disc needs to have good drawability whereas that for producing the rim requires a good flange ability. Flash butt welding for closing the rim is a high heat input process leading to a wide area with modified microstructure and hence properties (see Fig. 26). This is a concern when using high strength steel especially with regard to possible softening in the HAZ.

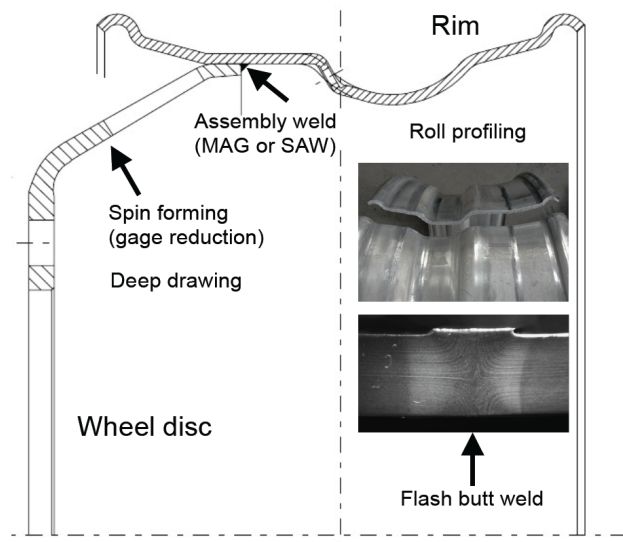


Fig. 26 Typical truck wheel design and involved key manufacturing processes

Over the last two decades the material used for the production of wheels already evolved from mild steel to HSLA and more recently to multi-phase steel. In the beginning of this evolution the only dimensioning principle was the fatigue resistance of the wheel while all other requirements such as stiffness and impact resistance were implicitly satisfied due to the high material thickness in disc and rim. However, the increased fatigue strength provided by high strength steels and the resulting possibility of reducing thickness of disc and rim also involve structural optimization to maintain stiffness and impact resistance. The theoretical lightening potential of higher strength steels as compared to 350 MPa HSLA steel is listed in Table 1. DP steel is favorable for the disc drawing process by its relatively low initial yield strength. Upon drawing it avoids local thinning due to its pronounced hardening characteristics. Ferritic-bainitic (FB) and bainitic (B) steels on the contrary have relatively high yield strength but expose good flange ability due to the fine-grained and homogeneous microstructure. FB and B steels for wheel applications are essentially similar to the steel grades used for truck frames. They comprise low carbon content and good hardenability out of the welding heat so that HAZ softening can be avoided even after the high heat input by flash butt welding. DP steel on the contrary is much more sensitive to welding heat input. Considering MAG welding as a standard joining technique for wheel assembly principally the strength of the weld increases with increasing the base metal strength. When producing a single-side welded lap joint the use of low strength welding wire such as OK Autrod 12.51 is preferable over high strength welding wire. The softer wire provides a higher ductility in the highly stressed root area of the weld metal.

Table 1 Weight reduction potential of high strength steels for wheels

Steel grade	Tensile strength/MPa	Fatigue limit/MPa	Weight reduction potential/%
HSLA340	420–540	210	0
FB450	450–550	250	12
FB600 / DP600	580–700	275	19
B800 / DP800	780–920	360	33

Note: HSLA: ferritic-pearlitic, FB: ferritic-bainitic, B: bainitic, DP: ferritic-martensitic microstructure

In DP steel hardness in the outer HAZ drops marginally for DP600 and up to 50HV for DP800 [7]. In the inner HAZ hardness peaks are observed with an increase of around 100HV above the base hardness. A problem that has been reported by some wheel manufacturers when MAG welding gage reduced high strength steel rims is burn-through causing leaks. Wheels containing this defect have to be scrapped.

When using autogenous laser welding, the hardness characteristics of the HAZ in these steel grades are distinctively different compared to MAG welding. HAZ softening is not observed due to the rather low heat input of laser welding. The hardness continuously increases from the base metal to the weld center. The actual peak hardness depends on the carbon content, the material thickness and the actual heat input [15].

Therefore, laser welding should be considered as an alternative technology in production of high strength wheels extending the current limitations imposed by conventional welding techniques. Laser welding can be used for butt-welding the ring, which is formed into the rim, thus replacing flash butt welding. In this approach both ends of the pre-formed ring are first laser-cut then positioned to zero gap and finally laser butt-welded. A dual-use laser head performing cutting as well as welding has been developed and is currently being applied in coil joining machines (see Fig. 27) [16]. The advantage of this alternative process in addition to the low heat input is that flattening of the ring end is not necessary. The round rolled ring ends are clamped and both ends are cut to precision by laser. Cutting scrap removal as well as fume and dust evacuation is integrated in the machine. Subsequently the cut ends are brought to contact with zero gap and the same head welds them together (see Fig. 27). The laser welding process does not produce any over-thickness so that post-weld machining is obsolete. This process is already being applied in coil welding machines where it successfully replaces flash-butt welding. Preliminary trials with laser-welded rims have indicated significantly improved fatigue strength of the welds as compared to flash-butt welded reference parts.

A fully automatic stand-alone production cell for wheel assembly welding by laser has been designed, as shown in

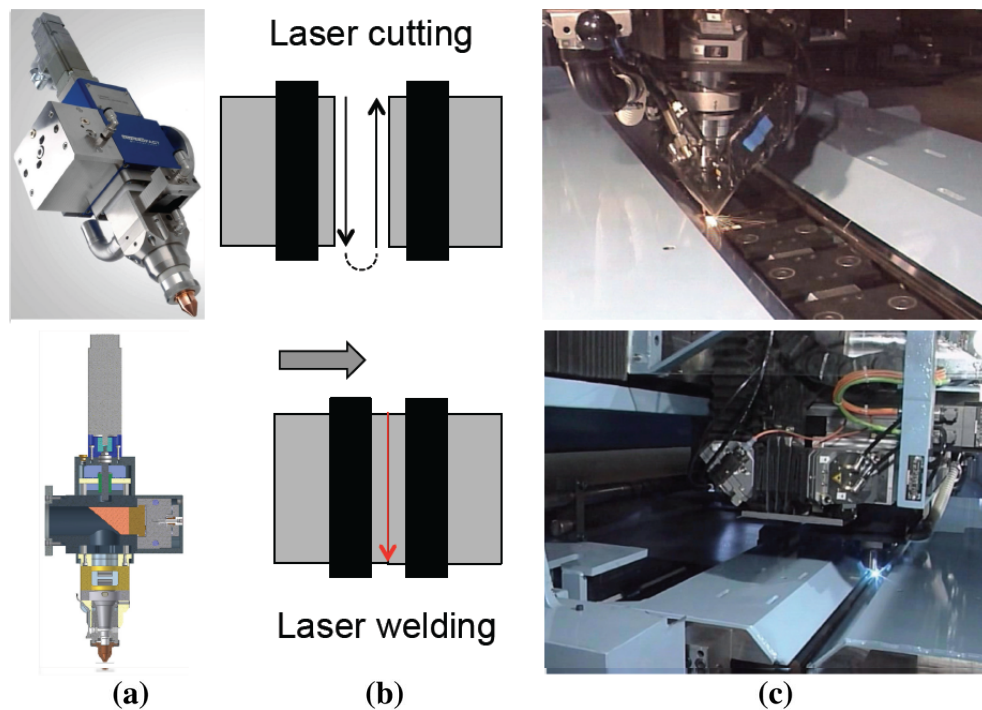


Fig. 27 Principle for laser-based wheel rim welding: combined laser cutting & welding head (a) and cutting-welding process sequence (b, c)

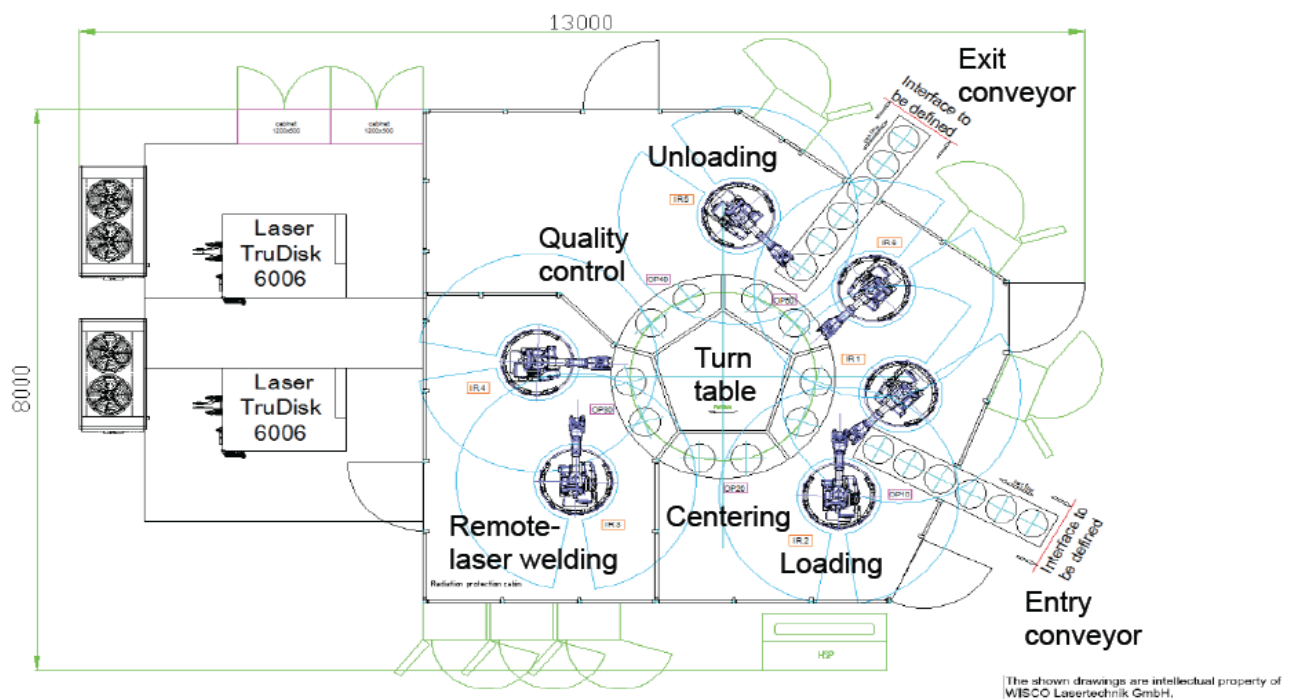


Fig. 28 Concept of a fully automatic stand-alone remote-laser welding cell for assembly welding of wheels

Fig. 28. In this concept press-fitted rim-disc pre-assemblies are delivered to the welding cell by conveyor. Handling robots place pre-assembled wheels into jigs mounted on a turntable. Subsequently the wheels are automatically

positioned for remote-laser welding occurring in the next station. The weld seam is then subjected to quality control by a seam geometry sensor. Finally robots remove the welded wheels from the jig and place them on an exit

conveyor. The cycle time of this remote-laser welding scenario is competitive with that of traditional manufacturing equipment. For a reference truck wheel size a cycle time of 3 s has been determined which is fully competitive with established conventional wheel production systems.

5 Conclusions

The various examples discussed in this paper have indicated that for major weight contributing components of commercial vehicles a weight reduction of 20%–30% is possible by using ultra-high strength steels. These steels are nowadays widely available in China from domestic production and in world-class quality.

During development of these high strength steel grades particular attention has been paid to adapt specific properties as to comply with the subsequent manufacturing processes during vehicle making. This particularly concerns formability and weldability. When bendability and flange ability are the dominating forming modes, fine-grained steels with homogenous (single phase) microstructure are the best choice. For high strength steels with good drawability, the best option is steels with fine-grained multi-phase microstructure. With regard to good weldability the focus is primarily on low carbon content (rather than low carbon equivalent) and preferably the carbon content remains below 0.1%.

For the production of structural components in commercial vehicles, roll forming is an efficient and versatile manufacturing technology. Recent development of flexible roll forming allows increasing the geometrical complexity of such components so that the application potential is further enhanced.

Press hardening has been showing its impressive potential in reducing weight and improving structural integrity of passenger vehicles recently. This potential and existing know-how can be readily transferred to commercial vehicle production. Significant activities are ongoing in the Chinese steel industry to improve the intrinsic properties of press hardening steels.

Laser welding has shown its merits in several ways as assembly welding technique and also in the production of tailor-made semi-products such as tailor welded blanks, coils, tubes, or profiles. Laser welding facilitates the use of high strength steel in commercial vehicle production due to its low heat input. It contributes to weight reduction by reducing or omitting material overlapping and reduces cost by its high productivity. The use of laser-welded semi-products offers further significant benefits. In this case the traditional processing chain (first forming then welding) is inverted saving not only weight but also

entire processing operations together with their specific investments.

Smart combinations of technologies such as roll forming, laser welding and press hardening provide much enhanced optimization potential in terms of weight reduction, functionality and cost reduction. To exploit this enhanced potential and to master the increased complexity of such technology combination designers, material engineers, manufacturing experts and also commercial professionals have to work closely together in a holistic approach.

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Light weighting opportunities and material choice for commercial vehicle frame structures from a design point of view

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Abstract This paper focuses on an estimation of light weighting opportunities for the frame structure of commercial road vehicles. This estimation is based on simplified static load cases which play a predominant role for the dimensioning of a frame structure and therefore these simplifications are not putting the general validity of the conclusions into question. A comparison of different materials under this scenario shows that light metals do not show any weight reduction advantage in comparison to steel while a material-independent topology optimization has more weight reduction potential for the frame structure than a simple change of materials. Considering the constraints of part complexity which is directly linked with production and assembly cost, the ladder frame structure has become the current state of the art design. Thus the paper also puts a spotlight on basic rules of node design and vertical load induction in order to keep the weight of such a design as low as possible. Practical examples from manufacturers show that the weight of a commercial

vehicle could be reduced by 10% and main parts of the frame structure could be reduced by 30% using high strength steel in combination with innovative production methods like roll forming.

Keywords Ladder frame · Light weighting · Commercial vehicle · Node design · High strength steel · Profile section · Vertical bending · Topology optimization

1 Design requirements for frame structures

The frame structure of a commercial vehicle to which all parts and modules are attached is the central interface of the entire vehicle. It is usually produced in high volumes for commercial road vehicles, which are completed by the original equipment manufacturer (OEM) with a cabin, axle and power-train modules to a drivable chassis. This drivable chassis is then completed with different superstructure variants by small and mid-size companies in low volume production depending on the special use of the vehicle. Thus the frame has to be easily adaptable for different kinds of superstructures and has to bear different load spectra imposed by these different types of superstructures.

The main load case for commercial vehicles is vertical bending. For the calculation of this load case the truck can be reduced to a 2-dimensional (2D) static model of a beam resting on two supports, which is vertically bent by a single or evenly distributed vertical load originating from the superstructure and the cargo. Dynamic forces caused by road bumps as well as abuse such as vehicle overloading are incorporated into the static model by multiplication of the static load with an impact factor which is based on experience. This factor is usually assumed to be 1.3 for conventional road vehicles in Western Europe, but it can be

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as high as 2 to 3 in emerging markets. It also depends on local market requirements and customer behavior.

The frame structure has to be flexible to accommodate torsion movements with deformation angle up to 20° especially for the use in construction or mining areas. In other cases it is combined with stiff superstructures such as boxes. In these cases the deformation angle of the frame usually does not exceed 2° , which is standard for paved road while the main share of the torsion is taken up by the axle suspension [1]. The assembly of hang-on parts as well as cables has to be easy-going. Also coating and corrosion protection of the structure should be feasible in a simple process with low cost.

Experience reveals that the optimal, i.e., the most flexible and cost efficient design for a commercial vehicle structure concerning the aforementioned requirements is the so-called ladder frame structure. It consists of two longitudinal beams with an open U-shaped section, which are laterally connected by preferably equidistant cross members with either closed or open sections. These give the whole construction in the planar view the typical ladder shape. In some special cases the longitudinal beams need to be cranked, e.g., for semi-trailers or dumptrucks, providing locally increased bending stiffness by a locally expanded section area especially at areas of high punctual load induction. Another possible local reinforcement could be realized by inserting reinforcement plates [2, 3].

2 Comparison of lightweight potential of various materials

The choice of the best lightweight material has to be made in the context of the design requirements and the load spectrum imposed to the structure. The lightweight potential has to be shown within constraints given by the material itself, the useable designed space and the manufacturability of real parts. An overall cost estimation should not be reduced to the material itself, and it should also consider production, assembly, tooling, maintenance and other cost. Accordingly, it should reflect its proper share on the total cost of ownership to the customer.

An IISI study [4] conducted by the Forschungsgesellschaft Kraftfahrwesen gives a detailed comparison of the mass reduction potential of steel and aluminum for different components of a car body under different load case scenarios. Although the overall weight reduction potential of aluminum is higher than that of high strength steel (HSS) in comparison to a mild steel reference structure, it very much depends on the main load case of a specific component whether a particular weight reduction advantage of aluminum vs. HSS can be found for this component.

The predominant load case for commercial vehicle frames is vertical bending which can be reduced to a simple model of a beam resting on two supports with the distance l equivalent to the wheelbase of the vehicle with one point load F in the middle reflecting the “worst” static load case (see Fig. 1). The profile section should be invariable according to its height h and width b given the assumption that there is only a limited designed space and no material should take advantage by more designed space in comparison to other materials. The only variable should be the required thickness t of the profile section and the material properties, i.e., yield strength R_e and density ρ . Without harming the general validity of this approach we can also assume $h = b$ to make the calculation as simple as possible.

The section area A can be estimated as

$$A \approx 3bt. \quad (1)$$

The second moment of inertia I is mainly depending on the contribution of the flanges which can be estimated as

$$I \approx 0.45b^3t. \quad (2)$$

The section modulus W results as

$$W = \frac{2I}{b} = 0.9b^2t. \quad (3)$$

The maximum bending moment M that occurs in the middle of the beam at the position where the load F is imposed can be estimated as

$$M = \frac{Fl}{4}. \quad (4)$$

The maximum stress σ results as

$$\sigma = \frac{M}{W} = \frac{Fl}{3.6b^2t}. \quad (5)$$

We assume for a simple static load case that the maximum stress σ should not exceed the yield strength R_e of the material. If we set $\sigma = R_e$ we can calculate the required thickness of the profile section

$$t = \frac{Fl}{3.6b^2R_e}. \quad (6)$$

The required thickness gives us the required mass m of the beam

$$m = \rho A l \approx 3\rho b t l \approx \frac{5\rho F l^2}{6b R_e}. \quad (7)$$

So the required mass is proportional to the ratio of the density and the yield strength of the material, and it can be estimated as

$$m \approx \frac{\rho}{R_e}. \quad (8)$$

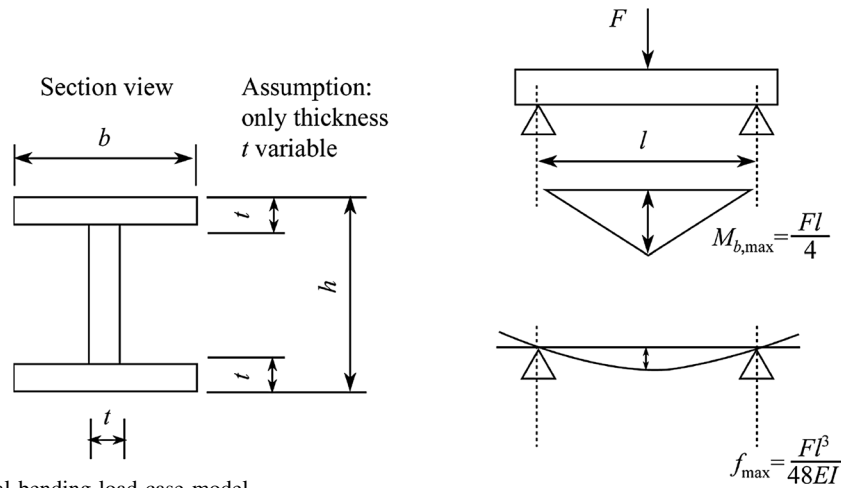


Fig. 1 Simplified vertical bending load case model

A comparison between two materials on the basis of the necessary mass (thickness) needed to bear the maximum force is represented by the ratio λ_{mR}

$$\lambda_{mR} = \frac{\rho_1 R_{e2}}{R_{e1} \rho_2}. \quad (9)$$

This scenario is applied under the assumption that the only limit is the strength of the material neglecting constraints given by the elastic deformation. If a certain elastic deformation is exceeded, moveable parts as in tautliners or even simple tailboards could be jammed. So under real-life conditions the maximum deformation limit has to be set. The maximum deformation f in the middle of the beam results as

$$f = \frac{Fl^3}{48EI}. \quad (10)$$

where E stands for the Young's modulus, i.e., the stiffness of the material. Given that a certain level of deformation should not be exceeded, the required thickness can be calculated as

$$t = \frac{5Fl^3}{108Eb^3f}. \quad (11)$$

This leads to a required mass

$$m = \frac{15\rho Fl^4}{108b^2Ef}. \quad (12)$$

So in this case the required mass is proportional to the ratio of the density and the Young's modulus of the material, and it can be estimated as

$$m \approx \frac{\rho}{E}. \quad (13)$$

A comparison between two materials on the basis of the necessary mass (thickness) needed not to exceed a bending limit is represented by the ratio λ_{mE}

$$\lambda_{mE} = \frac{\rho_1 E_2}{E_1 \rho_2}. \quad (14)$$

Table 1 contains an overview over the mechanical properties and the lightweight potential of different materials. Mild steel S235 is the reference and λ values below 1 are indicating better performance.

Looking only at the ratio of necessary mass and strength λ_{mR} , high strength steels and light metals are advantageous. Aluminum is on the same level like high strength steel. To limit the maximum bending to a certain value (λ_{mE}) light metals need more mass with the exception of carbon fiber reinforced plastics (CFRP). In this stiffness-driven case, the use of high strength steel does not lead to an advantage as compared to mild steel. Important aspects like material optimized design, metal fatigue especially around joining areas, cost, recycling, etc., have been neglected. The new HSD 700 HD steel grade introduced by the ThyssenKrupp subsidiary Hoesch Hohenlimburg [5] opens new lightweight potential for ultra-high strength microalloyed steel grades with high ductility (approximately 20% elongation)

Table 1 Comparison of material properties and light weighting potential

Material	Yield strength (R_e)/MPa	Young's modulus (E)/GPa	λ_{mR}	λ_{mE}
S235	235	210	1.00	1.0
S460 M	460	210	0.50	1.0
S700HD	700	210	0.30	1.0
EN-GJL200	200	100	1.10	1.9
AlMgSi T6	160	70	0.50	1.0
MgAl6Zn	175	44	0.30	1.1
GF-EP (50% GF)	270	37	0.20	1.4
CF-EP (50% CF)	330	120	0.16	0.4
Ti	250	105	0.50	1.1

and low carbon content (maximum 0.06%). These excellent material properties could be reached by using an innovative low-carbon steel chemistry in combination with increased niobium microalloying.

3 Geometry-driven lightweight construction

By only varying the section with the same material the weight changes proportionally to the section area. The goal is to choose the optimal geometry to reach the maximum load capacity with minimal material use – independent from any specific material. One main constraint for this optimization method is the increasing risks of buckling the thinner the sections are designed [6]. Without putting the general validity in question, a simple model of a cantilever beam can be used to demonstrate the lightweight design potential.

A round full material section, which remains constant over the full beam length, is taken as a reference to start with (see Fig. 2). In order to save weight, the first step would be changing the section in a way that material use is minimized while keeping the section modulus W on the same level. The example shows that the use of a U-shaped profile can reduce the weight to one third of the reference. Further weight reduction would be theoretically possible by a further extension of the designed space and a further reduction of the thickness. Yet an easy and cost efficient design would not be realistic because of buckling and other higher degree stability problems.

The next step would be a change of the section over length in order to reach a homogeneous maximum allowed stress level σ for optimum utilization of the material strength. The manufacturing of a cranked beam with variable sections is usually done by welding separate flanges on a web. German trailer producer Schmitz

Cargobull [7] has recently introduced flexible roll forming as a new manufacturing method for the series production of semi-trailer beams. This innovative manufacturing method avoids welds in highly stressed areas and reduces thermal deformation leading to residual stress.

Finally, the optimum solution would be the replacement of the web, which is still showing an unequal stress distribution. This can be achieved by struts leading alongside the areas of high stresses, which have been identified by a finite element analysis. In comparison to the full section reference this would diminish weight to less than 10% of the reference section. From an assembly point of view, however, this solution is not practical because the web is also needed to fix many attachment parts along the side member.

The more elaborately the lightweight structure is designed, the more important the profound knowledge about the load spectrum in real-life use. This is because the structure becomes increasingly vulnerable against any load that has not been considered within the optimization loop. There are already several studies proving that the aforementioned lightweight potential assumptions based on simplified theoretical models can be achieved under real-life conditions. A lightweight design study for a vehicle sub-frame conducted by ThyssenKrupp Steel Europe [8] shows that advanced high strength steel in combination with innovative semi-finished parts such as tailored products can achieve almost the same weight reduction as an advanced aluminum design, yet at half the cost. Swedish steelmaker SSAB demonstrated in several lightweight studies for trucks and trailers a weight reduction potential of more than 20% by using advanced high strength steel in the structure [9]. This comes at very moderate material cost increase. This moderate cost increase however is over-compensated during in the vehicle use phase due to fuel savings and higher loading capacity.

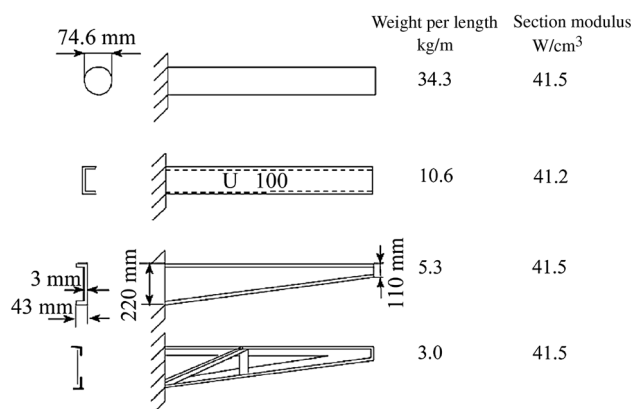


Fig. 2 Different stages of topology optimized mass reduction for a cantilever

4 Node design considerations

Node design is the crucial point in terms of lightweight performance of constructions consisting of different profiles. Most structural failures occur in areas where parts are joined though the reasons for failure can vary. In many cases the material itself is not the origin of the problem. Yet the joining process and the design of the joints offer many potential risks lying in the designed topology. Following basic rules for the design of different node types can minimize these risks.

The commonest node type is the intersection between a longitudinal beam and a cross member. When these parts are joined it is very important that free warping of the flanges is possible when the structure is loaded.

High stress peaks will occur in the weld if welding blocks the free movement of the flanges under load (see Fig. 3). Consequently, fatigue cracks will occur after a short time. The best solution is to weld only the webs of both profiles as indicated in Fig. 4.

The same rule is applied for vertical struts. It is also very important that the joining area of the two profiles does not create a locally closed section on top of an entirely open profile section (see Fig. 5). This will lead to an abrupt change in stiffness and therefore cause stress peaks in this area.

Another important aspect concerning vertical loads being introduced into open profile sections is an additional torsion moment caused by this vertical load. The larger the distance of the vertical force line from the shear center, the higher the torsional moment induced by the vertical force becomes (see Fig. 6). Ideally, vertical forces should be introduced close to the shear center, e.g., by attaching consoles close to this point.

In some cases local reinforcements of open profiles are necessary to support it against collapsing under a high single load. Web plates should then be placed in a way that the profile section is not partially closed to avoid abrupt changes in stiffness (see Fig. 7).

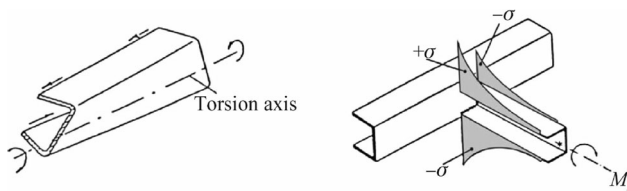


Fig. 3 Stress peaks caused by blocking free warping of the flanges under torsion [10]

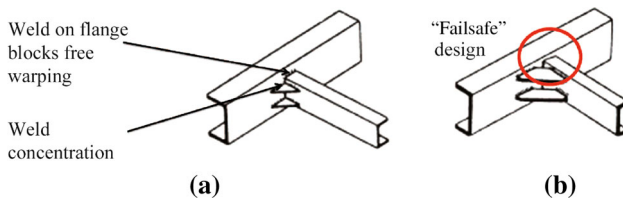


Fig. 4 Inferior **a** and superior **b** cross member attachment [11]

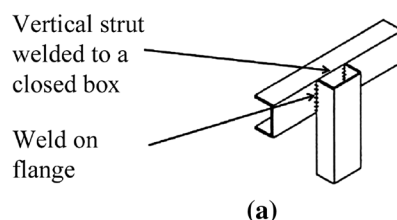


Fig. 5 Inferior **a** and superior **b** vertical strut attachment

The Brazilian mining company Companhia Brasileira de Metalurgia e Mineração (CBMM) conducted a design change of their dump trucks by upgrading from mild steel to high strength niobium microalloyed steel having yield strength above 700 MPa and accordingly reducing the part thickness. Furthermore, weld concentration and stress peaks in welded areas were eliminated by a design change.

A weight reduction of more than 1 900 kg was achieved leading to an increased loading capacity of 1.5 t (see Fig. 8). Higher cost of the upgraded steel and manufacturing caused a price increase of the truck. However this additional cost could be compensated within less than one year of operation because of increased loading capacity, reduced fuel consumption and reduced consumption of tires.

5 Achievements by Chinese truck manufacturers

Dongfeng Motor Co. realized several weight reducing solutions over the last years exploiting design changes as well as material upgrades. Topology changes in the main frame and the angle sheet achieved weight losses of around 84 kg and 96 kg, respectively. The use of high strength steel in the frame area has been established to the following levels:

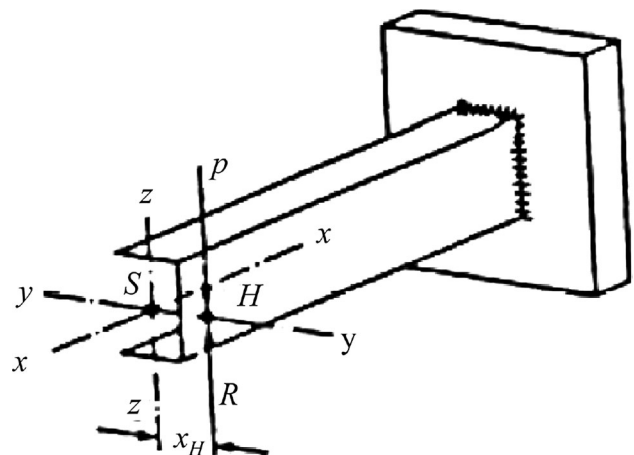
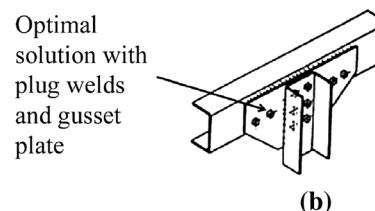


Fig. 6 Position of the share centre of a U-shaped section



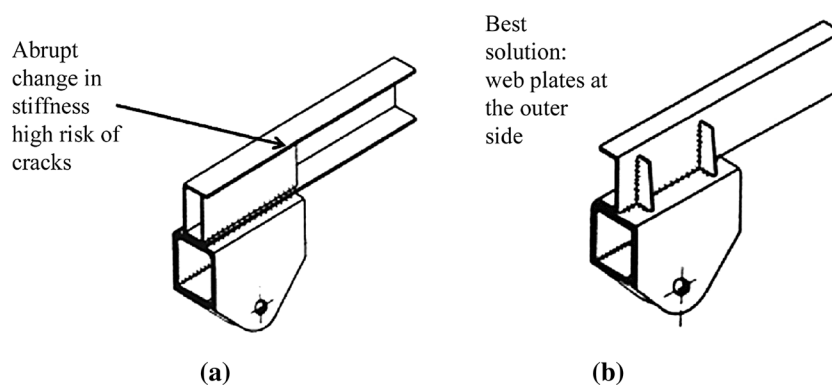


Fig. 7 Inferior **a** and superior **b** solution for a vertical reinforcement of an open section



Truck (Actros 4844, model 2010) = 11 074 kg
 Dumper + liner (Rossetti, model 2010) = 7 426 kg
 Total weight = 18 500 kg

(a) Conventional design



Truck (Actros 4844, model 2013) = 11 530 kg
 Dumper + liner (Rossetti, model 2013) = 5 470 kg
 Total weight = 17 000 kg

(b) Optimized design

Fig. 8 Weight reduction of a dump truck by upgrading to high strength steel



Fig. 9 Weight reduction of 250 kg in a dump truck by upgrading to D700L steel grade (Dongfeng)

- Longitudinal beam: 600–700 MPa
- Cross beam: 510–600 MPa
- Brackets: 440–510 MPa

The weight reduction achieved by this material upgrade from originally conventional carbon steel is in the order of 150 kg.

In dump trucks the frame beam gages could be subsequently reduced from originally (8 + 8) mm to (8 + 6) mm and (8 + 4) mm. A further tensile strength increase to 1 200 MPa by using heat-treated steel allowed applying 8 mm single gage beams. This brings a 25% (140 kg) weight saving as compared to the (8 + 4) mm beam



Fig.10 Weight reduction of 150 kg by using HSS in the frame structure (FAW)

Table 2 Light weighting achievements in various FAW trucks

Model	Applied optimization	Weight reduction
J5M	Reduce height of HSS beam to 280 mm from former 320 mm	21 kg/m
J5M	Reduce gage of HSS beam to 7 mm from former 8 mm	6.6 kg/m
J5K	Use of single-gage frame design	21.5 kg/m
J5M-8 × 4	Lightweight technology and batch production	700 kg

structure. However the significant strength increase by heat treatment did not reflect in a similar increase of fatigue resistance.

The weight of dump trucks could be reduced by up to 250 kg when replacing the formerly used D510L steel grade by D700L ultrahigh strength steel for the beams in the dumper. The replacement of steel grade Q235 by thinner-gaged high strength steel for the box section resulted in a weight reduction of 1 840 kg (see Fig. 9).

The HSS of 500 MPa minimum yield strength was developed by Baoshan Iron & Steel Co. Ltd. for longitudinal beams and applied in a newly designed truck by the First Automobile Works (FAW). Compared with traditional 16Mn steel, yield strength has been increased by 43% and the fatigue strength increased by 44%. The current use of 500 MPa steels for single gage beams reduced the weight by around 150 kg (see Fig. 10). Several other achievements of weight reduction at FAW commercial vehicles could be realized, as shown in Table 2.

The application of roll-formed beams made from steel grade 700L with gage of 10 mm could replace conventional (8 + 5) mm design resulting in a weight reduction of 29%. FAW also started using ultrahigh strength steel of 700 MPa yield strength (grade 900L), which will be the priority for the commercial vehicle construction in the future.

6 Conclusions and outlook

In commercial vehicle frame structures, high strength steel shows the most attractive combination of weight saving potential and cost. In order to achieve the maximum lightweight performance with regard to the entire structure,

the main goal is to avoid potential performance losses due to local effects especially in connecting areas. While in Europe high strength steel such as the S700 grade is already widely used in commercial vehicle frame structures, vehicle manufacturers in the emerging markets are recently intensifying their research and development activities concerning the application of ultrahigh strength steel grades. Close cooperation with the local steel mills has been established in China. A joint and comprehensive development comprising the whole process chain from the metallurgy down to the final product led to impressive weight saving results in the vehicle structure. This came without compromising manufacturability like forming and welding and keeping the overall costs on an acceptable level. Finally, it is the task of material suppliers and vehicle manufacturers to convince their customers, i.e., the truck operators of the benefits of lightweight design. This can be achieved by demonstrating that lightweight design does not lead to any loss of robustness in the daily operation of the vehicle. Field trials have demonstrated that the cost of ownership actually decreases with weight-optimized commercial vehicles. Modern high strength steel grades provide the best potential in this respect.

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Application potential of high performance steels for weight reduction and efficiency increase in commercial vehicles

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Abstract The fast-growing economy and the gradually established highway system have boosted the road transportation for both passenger and cargo over the last decade in China. From 2000 to 2010 Chinese GDP increased by around 10.15% annually and the sales of medium and heavy trucks by around 18.87% (sales increased from 0.2 million in 2000 to 1.3 million in 2010) according to the National Bureau of Statistics of People's Republic of China. Today commercial vehicles consume almost the same amount of fuel as passenger cars in China although the number of commercial vehicles is only about one fourth of passenger cars. It is estimated that around 50% of imported fuel to China each year will be consumed by vehicle transportation. This situation will worsen fuel shortage problems in the long run and at the same time it is partially responsible for the ever-worsening air pollution in China. Due to the widespread

overloading in China, lightweight development in commercial vehicles has fallen far behind that of passenger cars with the consequences that Chinese commercial vehicles consume in average about 20% more fuel, especially the heavy trucks, compared to European models. Under these circumstances it is essential to reduce the vehicle fuel consumption and increase the transport efficiency. The key solution thereby is to implement lightweight design in commercial vehicles as it has been successfully practiced over the last decade in the passenger cars. This paper summarizes highlights given in presentations during the "International seminar on the application of high strength steels in light weight commercial vehicles" with the focus on the development and application of Nb alloyed high performance steels made for lightweight commercial vehicles.

Keywords Commercial vehicle · Fuel consumption · Light weighting · High performance steel · Nb-based metallurgy

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1 Introduction

The principle of steel-based light weighting is to replace mild steels by high strength steels and thereby reducing material thickness. The technologies and experiences gained in achieving weight reduction for passenger cars clearly demonstrate that steel remains the most economic and sustainable material for vehicle manufacturing [1]. Thereby Nb-based metallurgy is the most effective way to produce such steels with enhanced performance for light-weight vehicles [2]. Figure 1 shows the weight reduction potential with increasing steel strength in relation to the different loading cases [2]. Over the last decades the steel industry has already developed different kinds of hot-rolled

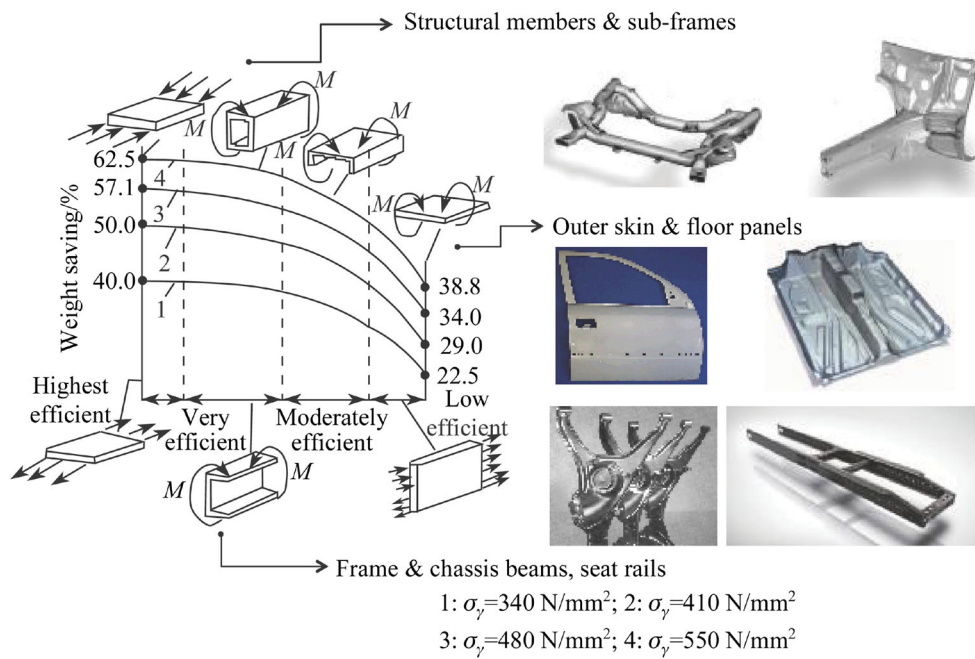


Fig. 1 Weight saving potential by substituting 200 MPa steel with high strength steels

Table 1 Hot-rolled high strength steels for application in the commercial vehicles

Micro-alloyed steels(yield strength)									
Grade	S315MC	S355MC	S420MC	S460MC	S500MC	S550MC	S600MC	S650MC	S700MC
Thickness/mm	1.5–12.0	1.75–12.0	1.9–12.0	2.0–8.0	2.0–6.5				
Width /mm	75–2 000	100–1 900							
Ferritic-bainitic steels			Dual phase steels			Martensitic steels			
Grade	FB-W 500		FB-W 600		DP-W600	MS-W 1000		MS-W 1200	
Thickness/mm	1.75–5.5		1.75–4.0		1.6–5.5	1.5–3.0			
Width /mm	100–1 900		100–1 650		100–1 550	600–1 400			

high strength steels for different applications in commercial vehicles (see Table 1). These high strength steels can be used effectively to substitute the conventional steels in components with the same or even enhanced functionality and simultaneously reduced thickness (see Fig. 2). In the initial phase of developing such high strength steels, carbon was considered to be the most economic and effective element leading to the relative high carbon content in such steels. However the practice has demonstrated that for the automotive application access carbon will deteriorate manufacturing properties like weldability and formability and it will have negative impact on the service performance of the components as well. Nb-based metallurgy provides the optimum solution in this respect due to its two

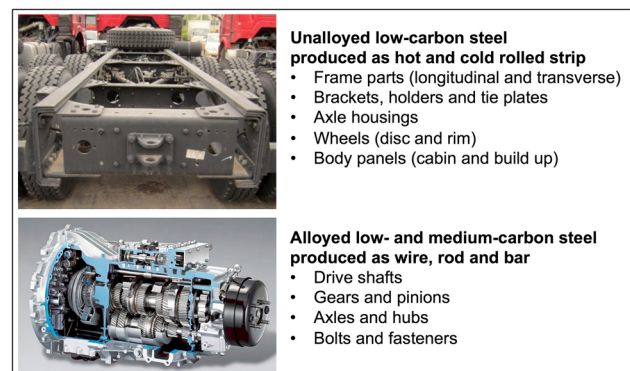


Fig. 2 Major components of commercial vehicles considered for application of high performance steel

fundamental effects of grain refinement and precipitation hardening [3, 4]. The latest developments and achievements presented at the seminar clearly demonstrated that how Nb-based metallurgy could be adopted to make high performance steels, specifically for commercial vehicles. High performance steels are characterized by enhanced material properties, improved processing behavior and finally better component functionality during service life irrespective of where the material is applied.

2 Enhanced properties of high performance steel by Nb microalloying

With original equipment manufacturers (OEMs) turning towards high strength steels for light weighting, steelmakers are being confronted with challenges of developing high strength steels, which not only meet the specifications in terms of mechanical properties but also suit the manufacturing processes in an established production chain. One of the important aspects to start the manufacturing process with very high strength steel is to have a steel coil with uniform properties and good flatness along the coil. The key solution to achieve uniform properties and good flatness of high strength steel coil is based on an appropriate alloying concept and precise process control. Experience gained at Baoshan Iron & Steel Co. Ltd. clearly confirmed the advantages of the Nb-based alloy concept in producing the micro-alloyed steel S460MC compared to the traditional Ti-based concept (see Fig. 3). The alloy containing 0.02% Nb achieved the same strength level of 460 MPa as the concept using 0.04% Ti. However the scattering range of strength in the Nb-based concept is less than 50 MPa while for the Ti-based concept it is more than 100 MPa. The large scattering in the material properties will be presented in the final components made from that steel. On the other hand it

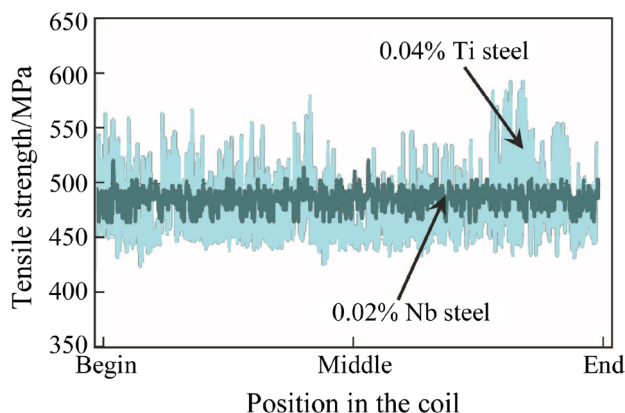


Fig. 3 Scattering of tensile strength in hot-rolled coil of S460MC depending on the applied microalloying concept

causes pronounced spring-back effect during the forming process making it more difficult and costly. In China it is quite common to produce micro-alloyed steels by using either Ti-based concepts due to alloying cost or Nb-based concepts. However the Nb micro-alloyed grades generally achieve much more uniform properties than Ti grades due to the fact that it is difficult to precisely control the right amount of Ti for precipitation hardening in order to achieve the specified strength because Ti also forms large precipitates or inclusions with N, S and P at higher temperature. Besides, such large Ti particles are often crack initiators during the forming process (see Fig. 4).

Recently Beijing Shougang Co. Ltd. has developed hot-rolled high strength steels with yield strength above 900 MPa for light weighting of commercial vehicle components. The alloying concept is based on low-carbon content and Nb–V–B microalloying processed to a microstructure consisting of bainite or/and martensite. Depending on the thickness and application requirements, thermo-mechanically controlled process (TMCP), TMCP/tempering or TMCP/quenching and tempering (QT) process can be applied. Uniform mechanical properties and good toughness in both transverse (trans.) and longitudinal (long.) directions of the coil have been achieved (see Table 2 and Fig. 5). In Table 2, A is total elongation; r is the bending radius; t is the sample thickness.

In order to achieve bainite and martensite in the microstructure of final products based on low-carbon alloy design, high cooling rate in combination with low coiling temperature below bainite or martensite start temperature is required. Due to this reason it is quite challenging to obtain good strip flatness especially with increasing thickness after hot rolling. Increasing the tempering temperature to reduce the residual stress caused by fast cooling or

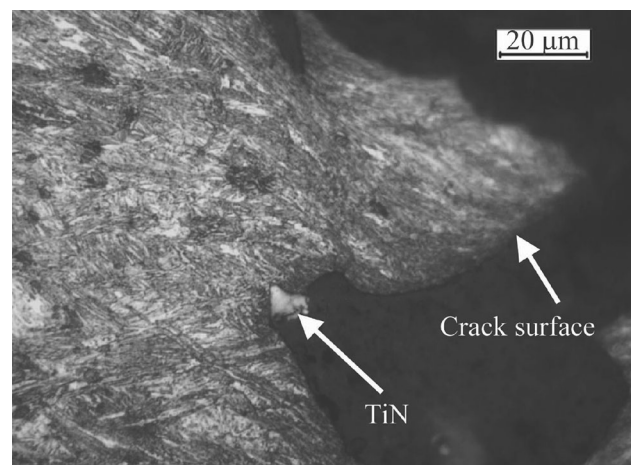
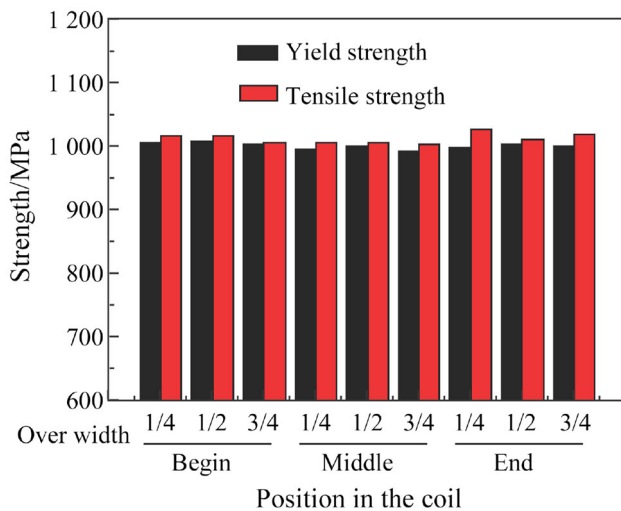


Fig. 4 Component cracking caused by large TiN particles during forming process of Ti micro-alloyed high strength steel

Table 2 Mechanical properties and toughness of hot-rolled high strength steel for commercial vehicles developed by Beijing Shougang Co. Ltd.

Gage (d)/ mm	Sample position	Yield strength / MPa	Tensile strength / MPa	A/%	Charpy energy/J				Bending test			
					Temperature=0 °C		Temperature=-20 °C					
					Sample 1	Sample 2	Sample 3	Sample 1	Sample 2	Sample 3	Bending angle /(°)	$r = 4t$
5.8	Trans.	944	1 066	12.8	65	67	64	—	—	—	90°	Ok
	Long.	946	1 059	14.2	—	—	—	52	54	53	90°	Ok

**Fig. 5** Uniformity of strength in hot-rolled coil with yield strength above 900 MPa produced by Beijing Shougang Co. Ltd. ($d = 5$ mm)

different phase transformations over the thickness solved this problem. The strength loss caused by the tempering effect on the bainitic and/or martensitic microstructure was compensated by increasing the Nb and V content in the steel providing additional precipitation strengthening. Through the alloy modification and process optimization, hot-rolled high strength steel with yield strength above 900 MPa can be produced showing very good flatness (see Table 3). Besides, low-carbon content and a favorable microstructure provide good weldability, toughness and formability.

This newly developed steel has been successfully applied in dump trucks, semi-trailers and mobile cranes reducing the vehicle weight. For instance in a new semi-trailer design (see Fig. 6) steel with 900 MPa yield strength was used to replace Q345 reducing the weight of the longitudinal beams with 60%. It was also applied in structural parts and walls of the truck body. Together with other lightweight design solutions in the suspension and wheels the total dead weight of the vehicle was reduced down to 4.9 t which was 40% less compared to the previous model. Up to now, two pilot vehicles have passed 180 000 km road testing. Fuel saving has amounted to 0.245 Yuan/km

and 44 000 Yuan/year. Besides, the transport revenue increases by 9 000 Yuan/year when the payload is increased by 2 t per trip. Accordingly, such ultra high strength steel brings benefits to the entire supply chain ranging from steelmaker to the end-user.

Special steels are widely used in the commercial vehicles, for example, in the power train and suspension area. The quality of special steels is one of the most important factors with regard to durability and performance of the vehicle. Micro-alloyed special steels and particularly case-carburizing steels can achieve higher load bearing capacity and improve the total performance. In this context two new alloying designs with Nb microalloying have been investigated to improve the high-end case-carburizing steel grade 18CrNiMo7-6 which is being standardly used for making high performance gear [5] (see Table 4).

One of the new alloy designs is aiming for higher performance with regard to future requirements on medium-sized and large-sized transmissions. Mn and Mo are increased for a better hardenability while Ni is reduced for cost reduction. Besides, a high Ni content can stabilize retained austenite in the case layer reducing its hardness. Nb microalloying is applied to restrict austenite grain coarsening during the carburizing process. Accordingly higher carburizing temperature can be applied to shorten the processing time and lower production cost. Furthermore, grain refinement results in higher toughness and fatigue strength. Besides providing fine grain size, appropriate microalloying in carburizing steel also reduces grain size scattering. This limits the distortion upon quenching and hence reduces hard machining efforts. The other new alloy design is aiming for lower total alloy cost due to significant reduction of the Ni alloy content, yet achieving similar performance as the reference grade 18CrNiMo7-6. Nb microalloying is applied for the same reasons as mentioned in the other new alloy design. The achieved mechanical properties of both newly designed case-carburizing steels indeed correspond to the postulated expectations (see Table 5).

As expected concept V₁ achieves much higher strength due to improved hardenability and at the same time results in a higher rotating fatigue limit due to grain refinement.

Table 3 Shape deviation after blanking of hot-rolled DQ steel ($d = 5$ mm) with yield strength above 900 MPa (steel produced by Beijing Shougang Co. Ltd.)

Blanking length/ mm	Flatness deviation in rolling direction/ mm	Flatness deviation in transverse direction/ mm	Straightness after blanking	Warping
6 000	0.1	0.2	<1 mm/1 000 mm	0

**Fig. 6** Lightweight semi-trailer made in China by high strength steels with yield strength above 900 MPa**Table 4** Chemical composition of Nb micro-alloyed case-hardening steels in comparison with standard 18CrNiMo7-6

Steel grade	w(C)/%	w(Si)/%	w(Mn)/%	w(Cr)/%	w(Mo)/%	w(Ni)/%	w(Nb)/%
Concept V ₁	0.26	0.12	1.46	1.23	0.54	0.91	0.03
Concept V ₂	0.21	0.25	1.17	1.15	0.21	0.22	0.04
18CrNiMo7-6 (1.6587)	0.15–0.21	≤0.40	0.50–0.90	1.50–1.80	0.25–0.35	1.40–1.70	

Table 5 Mechanical properties of Nb micro-alloyed case-carburizing steels in comparison with 18CrNiMo7-6 (hardened at 880 °C/2 h + oil/180 °C/2 h)

Property	Concept V ₁	Concept V ₂	18CrNiMo7-6
Tensile strength/MPa	1 758	1 182	1 182
Impact energy/J	47	55	80
Rotating fatigue limit $\sigma_{(50\%)}@N = 10^7$ MPa	722	491	510
Hardenability@11 mm /HRC	51	44	41
Hardenability@25 mm /HRC	50	36	36

The toughness remains at a good level in spite of the high tensile strength. Concept V₂ with reduced total alloy cost achieves similar properties compared to 18CrNiMo7-6. Toughness is reduced due to the much-reduced Ni content but still remains on an acceptable level. Gears made from both innovative case-carburizing steels have been benchmarked by running performance tests. In these tests gear tooth root fatigue and gear tooth flank micro-pitting were characterized as performance criteria. Concept V₁ is clearly

outperforming existing case-carburizing grades (framed area in Figs. 7 and 8). Alloy concept V₂ matches the performance spectra of existing case-carburizing grades despite its reduced alloy cost (see Figs. 7 and 8). In Figs. 7 and 8, Grade ML stands for the minimum requirement; grade MQ represents requirements which can be met by experienced manufacturers at moderate cost; grade ME represents requirements which must be realized when higher allowable stresses are desirable.

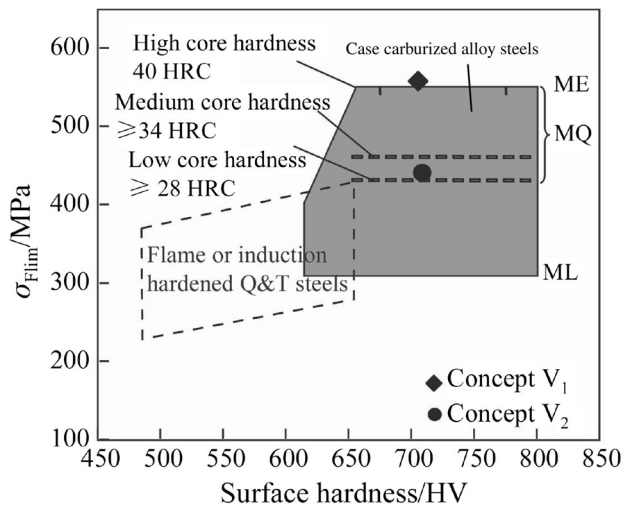


Fig. 7 Benchmarking of gear tooth root fatigue of innovative case-carburizing steels compared to the conventional alloys

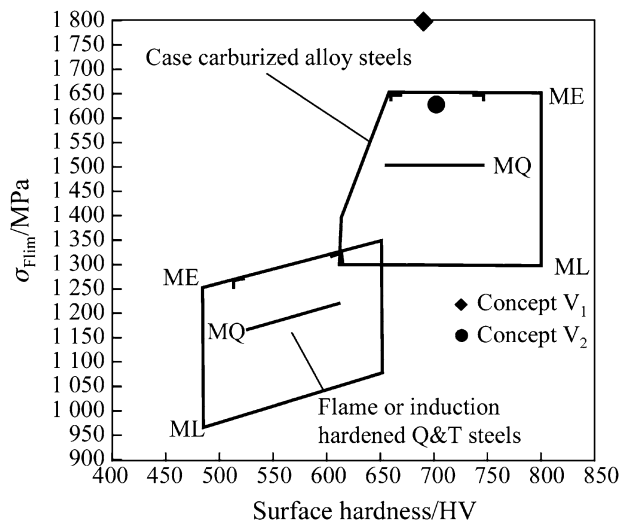


Fig. 8 Benchmarking of gear tooth flank micro-pitting of innovative case-carburizing steels compared to the conventional alloys

Pistons for truck engines are another example for the application of Nb micro-alloyed special steels. In the diesel engine of modern trucks, the operating temperature can reach up to 650 °C and the operating pressure up to 20 MPa. Due to this reason steel grade 42CrMo started being used recently to replace Al-made pistons. But surface oxidation and material softening reduce the performance of the steel due to high operating temperature. The modified steel grade

42SiCrMo with Nb microalloying (see Table 6) reduces scale forming by a factor of 10 compared to the standard grade 42CrMo under the same operating conditions [6]. Due to the synergy between Nb and Mo in such steel complex precipitates of Nb(Mo)C-type are much finer and more resistant to particle coarsening during high operating temperature. Accordingly the steel has 20% higher tensile strength and it is simultaneously more resistant to softening when exposed to high temperature.

3 Improved processing properties of high strength steels by Nb microalloying

The formability and weldability of steel need to be specifically considered with increasing strength. Both properties which are directly related to vehicle manufacturing have considerable impact on processing feasibility. Material failure occurring during welding or forming will reduce the production efficiency and consequently increase the production costs. Generally it is important to reduce the steel's carbon equivalent for good weldability. Increased carbon content in combination with low heat input causes high hardness in the heat-affected zone (HAZ) with the risk of cold cracking. Steel based on low-carbon content and Nb microalloying can effectively provide high strength and good weldability. Both hardness and toughness in the HAZ depend much on the heat input and cooling rate of the applied welding process. For a good combination of both properties it is important to define a process window in terms of heat input and cooling rate in order to limit the maximum hardness to below 350 HV and the transition temperature to below −40 °C. A narrow process window is related to poor weldability from the material side and difficult weld processing from manufacturing side. Reducing the carbon content from 0.08% to 0.03% and increasing Nb content from 0.06% to 0.09% in an innovative alloy concept for steel grade S500MC [7], the HAZ hardness could be significantly reduced over the entire range of heat input experienced by typical assembly welding processes (see Fig. 9). Such an alloying concept also allows a larger process window in terms of cooling rate after welding avoiding cold cracking and generally providing good toughness in the HAZ (see Fig. 10). For the steel grades S-MC up to 900 MPa yield strength, no preheating is required for the welding process if the heat input is adjusted within a reasonable range.

Table 6 Modified steel grade with Nb microalloying for the application of engine pistons in the truck diesel engines for the high operating temperature and pressure

Steel grade	w(C)/%	w(Si)/%	w(Mn)/%	w(Cr)/%	w(Mo)/%	w(Cu)/%	w(Nb)/%	w(Ti)/%
42SiCrMo modified	0.40–0.43	2.0–3.0	0.70–0.85	0.90–1.15	0.15–0.25	0.25	0.04	0.02

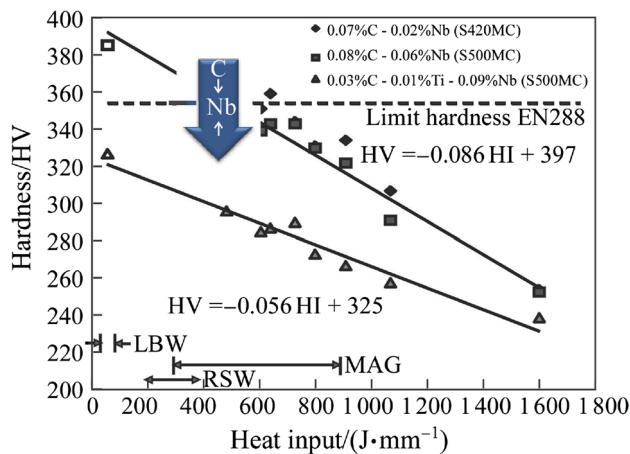


Fig. 9 Effect of heat input on peak hardness in the HAZ for various Nb-based alloy concepts of steel grade S500MC (LBW: laser beam welding, RSW: resistance spot welding, MAG: metal active gas welding)

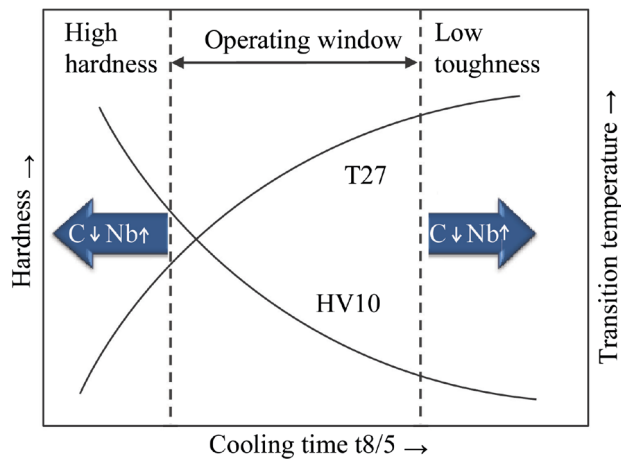


Fig. 10 Schematic influence of alloying strategies and cooling rate (heat input) on the operating window in terms of HAZ hardness and toughness

In many cases, modern high strength steels consist of a multiphase microstructure using the strengthening mechanism of transformation which is hardened to obtain hard phases like bainite, martensite and retained austenite embedded in a ductile phase such as ferrite. For such multiphase steels Nb microalloying has been increasingly applied to improve the homogeneity of the microstructure through grain refinement [8]. With reduced grain size, the banding structure of hard phases like martensite can be suppressed and the distribution of different phases is more homogeneous [9]. Besides, the hardness difference between hard and soft phases is being reduced, because Nb microalloying has a more profound strengthening effect on ferrite than the other hard phases like bainite and martensite. Such improvement in the microstructural details directly

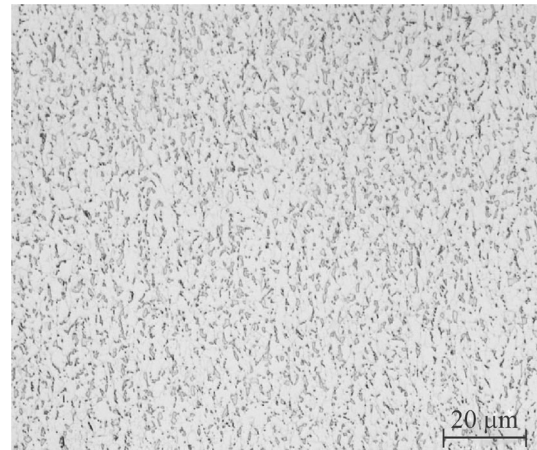


Fig. 11 Microstructure of hot-rolled FB600 steel developed by Benxi Iron & Steel Group Co. Ltd. for wheel rim application

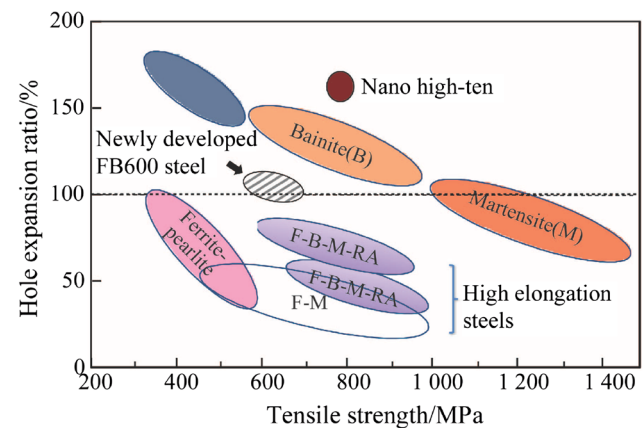


Fig. 12 Hole expansion ratio of newly developed hot-rolled FB600 compared to other commonly used automotive steel grades

leads to an improved forming behavior of the steel, especially during bending and hole expansion operations. Particularly these properties are important for the manufacturing of truck frames, structural reinforcements and wheels. This also reduces the sensitivity to the edge cracking of high strength steels during the forming process. Benxi Iron & Steel Group Co. Ltd. recently developed the hot-rolled ferritic-bainitic grade FB600 based on a low-carbon content and Nb microalloying for the application in lightweight wheels. Very fine and homogeneous microstructure consisting of ferrite (60%–70%) and bainite (30%–40%) is achieved. Thereby the ferrite grain size is as small as ASTM 13 (see Fig. 11). Apart from good mechanical properties (elongation above 30% with tensile strength beyond 600 MPa), this newly developed FB600 demonstrates excellent hole expansion properties of more than 100% (see Fig. 12) outperforming all existing DP steels. Due to such excellent properties this hot-rolled FB600 in gage of 4.5 mm has been applied for

manufacturing wheel rims helping to reduce the rim weight from 13.8 kg to 11.5 kg corresponding to a 16.7% weight reduction from the original wheel rim. Through precise control of inclusions and grain refinement, the customer fatigue requirements have been satisfied by reaching 1.1 million revolutions in a radial fatigue test.

4 Improving component functionality and service life by Nb microalloying

Nb microalloying has been increasingly used in the high strength steels to improve the service performance of components in passenger cars as well as commercial vehicles. For instance in press hardening (hot forming) steels, Nb microalloying can improve the toughness through grain refinement so that press hardened components will expose better crash behavior with higher energy absorption especially when the crash occurs in a low temperature environment. Another concern of OEMs is the delayed cracking induced by hydrogen embrittlement which can dramatically reduce the crash performance of press hardened components due to severe degradation of strength and toughness. Investigations revealed that Nb precipitates dispersed in the martensitic matrix had the ability of trapping hydrogen present in the steel and made it less diffusible. Thus it will less segregate to grain boundaries causing the typical intergranular fracture or material defects like large inclusions and microcracks which lead to local damage. This perception leads to the development of Nb alloyed press hardening steel. Adding 0.05% Nb to press hardening steel based on the alloy concept 22MnB5 resulted in more than three times higher critical fracture stress compared to the conventional steel under the same hydrogen charging conditions (see Fig. 13). It also lowered the ductile-to-brittle transition temperature thus leading to better low temperature toughness. Today press-hardening steel has become state of the art technology in car body engineering for passenger cars. Press hardening steel represents as much as 38% of the total body weight of the recent sports utility vehicle (SUV) model Volvo XC90 [10]. There is a clear trend to use press hardening steel (PHS) in the commercial vehicles for reducing weight and simultaneously increasing safety. This approach has been already implemented in light commercial vehicles, e.g., Ford Transit [11] as well as in full-size trucks, e.g., Scania.

Approximately 4 000 to 7 500 joining bolts are used for the assembly of commercial vehicles adding about 50–90 kg to the total weight of the vehicle. In conventional Chinese truck manufacturing 10.9 grade high strength bolts are used in the engine block and 8.8 grade for other applications. Replacing 10.9 grade bolts by ultrahigh strength bolts, such as 13.9 grade, 10% reduction

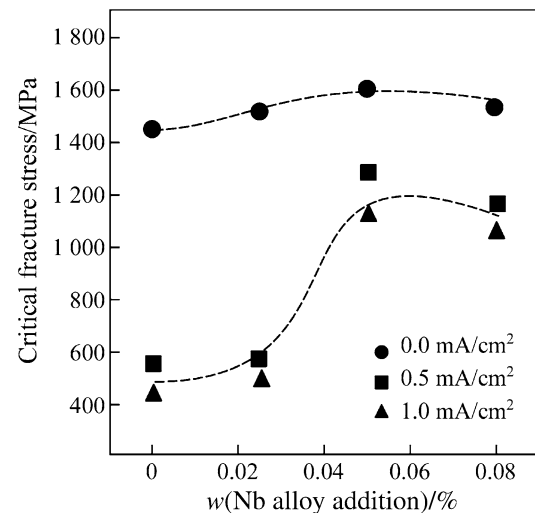


Fig. 13 Effect of Nb microalloying on the critical fracture stress of press hardening steel based on 22MnB5 under the same hydrogen charging conditions

of the joining bolt weight can be achieved while the strength is increased by 30%. However the major obstacle in using ultrahigh strength bolts is hydrogen induced cracking. Steel grade 42CrMo has been widely used in China for making high strength bolts. However the resistance to hydrogen induced cracking of this alloy is insufficient for the application. Modification of this steel grade by microalloying allows tolerating up to six times higher hydrogen content without causing severe hydrogen embrittlement. This is due to the hydrogen trapping effect of microalloy precipitates (see Fig. 14) [12]. With increasing tempering temperature, the amount of microalloy precipitates increases and so does the hydrogen trapping potential. However the hydrogen trapping effect decreases again when the tempering temperature becomes too high as this leads to precipitate coarsening by the so-called Ostwald ripening mechanism. Hydrogen testing under the identical conditions revealed that the conventional grade 42CrMo showed the typical intergranular fracture due to severe hydrogen embrittlement at lower hydrogen content. On the contrary, micro-alloyed grade 42CrMo exposed transgranular fracture at six times higher hydrogen content (see Fig. 15). Transgranular fracture generally occurs at a higher critical fracture stress than intergranular fracture. Microalloy and appropriate precipitate dispersion being a metallurgical remedy against hydrogen embrittlement lead to the development of steel grades for ultrahigh strength bolts in China. These have not only higher strength but also higher resistance to fatigue as well as to hydrogen-induced cracking (see Fig. 16). More than one million ultrahigh strength bolts made from steel grade 13.9 have already been used for different applications in China. Through the improvement of material properties, the

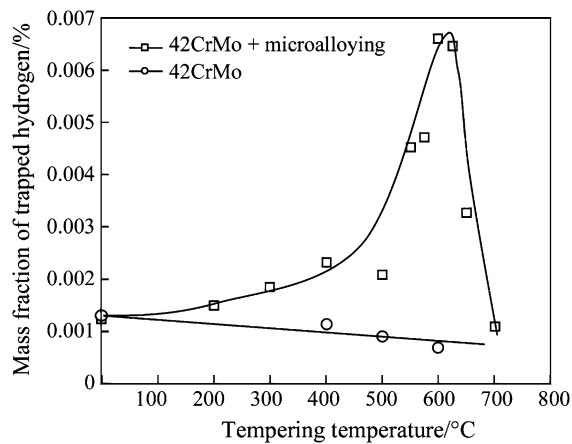


Fig. 14 Impact of microalloying on the hydrogen trapping effect of high strength bolts made from 42CrMo and tempered at different temperatures

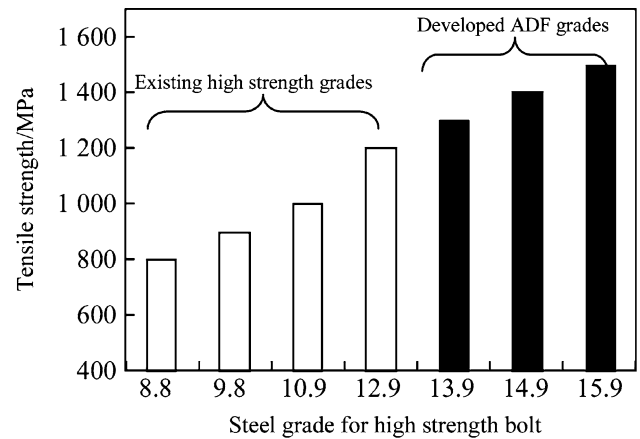
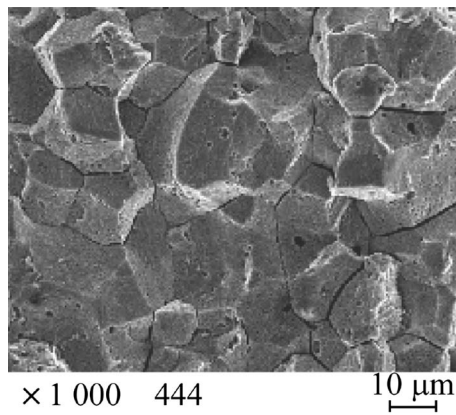
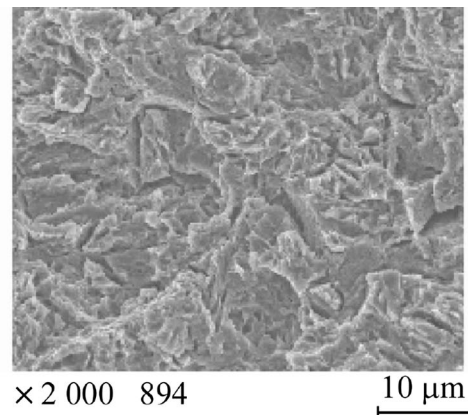


Fig. 16 Tensile strength of steel grades for high strength bolts developed in China



(a) 42CrMo intergranular fracture



(b) 42CrMo + microalloying transgranular fracture

Fig. 15 Effect of microalloying on the fracture appearance of high strength bolts made from grade 42CrMo after exposure to identical hydrogen charging conditions

functionality of the joining bolts and the safety of the vehicles have been significantly enhanced. It is noteworthy in this context that 60%–70% of the accidents caused by commercial vehicles in China are related to the broken joining bolts.

5 Conclusions

Due to pressing sustainability issues such as fuel consumption and air pollution in China, it is indispensable to increase the transport efficiency by reducing the weight of commercial vehicles thus increasing payload capacity. The key approach of implementing lightweight design in commercial vehicles is to use high performance steel for

manufacturing major components. The technologies and experiences gained in achieving weight reduction in passenger cars clearly confirm this approach and they are readily available in China to be transferred to commercial vehicles.

Lightweight design with steel is economical as it even often results in reduced cost. The weight reduction and hence lower consumption of material to manufacture components usually compensate the moderate price increase for high performance steel. Producing less but more profitable high performance steel is beneficial for the Chinese steel industry as well as for the environment in general. Regarding life cycle assessment steel has globally a better total emission balance than competing materials available for weight reduction.

Nb-based metallurgy has proven to be particularly beneficial when producing high performance steels for commercial vehicle applications. Such Nb micro-alloyed steels have superior properties with regard to manufacturing and also reveal better durability during the vehicle operation phase.

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Sustainable development of China's commercial vehicles

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Abstract Automobiles are the major contributor to fuel consumption and emission of pollutants. The growth of the vehicle fleet has also placed enormous pressure on China's energy supply and environment. Thus sustainable development of the Chinese automotive industry must pay significant attention to fuel-saving and emission-reduction of vehicles. Although commercial vehicles make up only about 20% of the entire automobile fleet, their contribution to energy-consumption and emission of pollutants is significant. Thus, priority should be given to fuel-saving and emission-reduction of commercial vehicles. As a result of concerted efforts by Chinese government, industry and enterprises, great progress has been made in technologies concerning new-energy, intelligent and lightweight automobiles. However, compared with developed countries, the level of lightweighting of commercial vehicles produced in China remains comparably low. This means that great potential for development of lightweight commercial vehicles in China exists and it will be an efficient path towards fuel-saving and emission-reduction.

Keywords Commercial vehicles · Fuel-saving · Emission-reduction · Lightweight

1 Introduction

The automotive industry plays a major role in fuel consumption and emission of pollutants. Yet its rapid growth in China in recent years has meant that the nation's energy supply and environment are under increasingly severe pressure. Commercial vehicles make up about 20% of China's total fleet of automobiles, but their considerable weight, high fuel consumption and long travel distances result in that they stand for nearly 50% of the total fuel consumption of all the automobiles in China [1]. Truck making represents only 17.5% of total production capacity for automobiles, while their particle emissions make up as much as 78.6% of the total automobile emission [2]. This is a serious problem. Therefore the sustainable development of China's automotive industry would not be possible without paying any attention to fuel-saving and emission-reduction.

2 Current status of China's commercial vehicles with respect to fuel-saving and emission-reduction and future perspective

According to the definitions provided in “Automobiles and Trailer Types—Terms and Definition” (GB/T 3730.1—2001), commercial vehicles are those with design and technical characteristics for the transportation of individuals and cargo, and can be classified into 5 types namely busses, trucks, semi-trailer towing vehicles, incomplete busses and incomplete trucks.

2.1 Changes in commercial vehicle fleet in China

Since 2005, the commercial vehicle fleet in China has grown rapidly along with increasing sales of automobiles.

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However, the ratio of the commercial vehicles to the total number of automobiles (excluding three-wheel vehicles and low-speed trucks) has gradually declined to around 20% [3] (see Fig. 1). In 2005, the total commercial vehicle fleet counted 10.272 million units, representing 32.5% of all the vehicles. After that, this share gradually declined. By 2010, the total commercial vehicle fleet counted 16.384 million units, representing 21% of all vehicles. By 2012, the total commercial vehicle fleet counted 21.844 million units, representing 20% of all vehicles.

2.2 Fuel consumption of Chinese commercial vehicles

Since the beginning of the 21st century, there has been rapid growth in total fuel consumption in China. It grew from 8.9×10^7 t in 2000 to 1.85×10^8 t in 2009, of which nearly 80% was accounted for by diesel and gasoline consuming automobiles [4] (see Fig. 2). Between 2000 and 2012, the automotive-related fuel consumption grew by a factor of 2.62 from 6.8×10^7 t to 1.78×10^8 t and an average annual growth rate of 8.36%. This annual growth rate was far higher than the average annual growth rate (6.5%) of total fuel consumption during the same period. Therefore, the automotive-related fuel consumption is a major factor for growth in China's total fuel consumption.

2.3 Emission pollutants by Chinese commercial vehicles

Between 2010 and 2012, the emissions of carbon dioxide (CO_2), hydrocarbons (HC), nitrogen oxide (NO_x) and particulate matters (PM) emitted by automobiles in China have been steadily increasing (see Fig. 3). The emission of CO_2 had increased from 2.67×10^7 t to 2.87×10^7 t at an average annual growth rate of 3.6%; the emission of HC had increased from 3.24×10^6 t to 3.45×10^6 t at an average annual growth rate of 3.3%; the emission of NO_x had increased from 5.37×10^6 t to 5.83×10^6 t with an average annual growth rate of 4.2%; the emission of PM

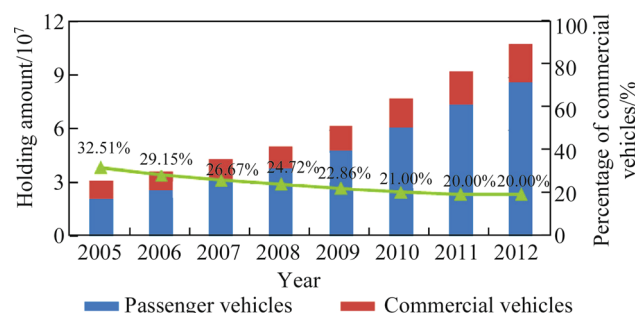


Fig. 1 Changes in total holdings of commercial vehicles in China since 2005 (Source: OICA website)

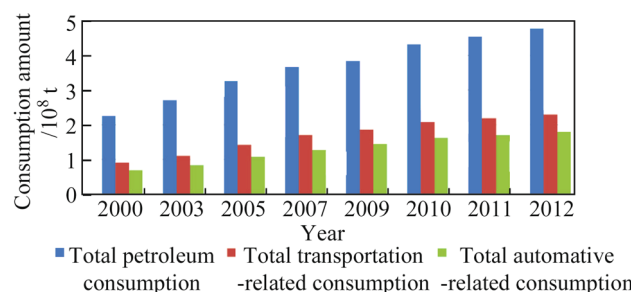


Fig. 2 Petrol consumption in China since 2000 (Source: “2014 Report on Development of China's Automotive Technology” by Society of Automotive Engineers of China)

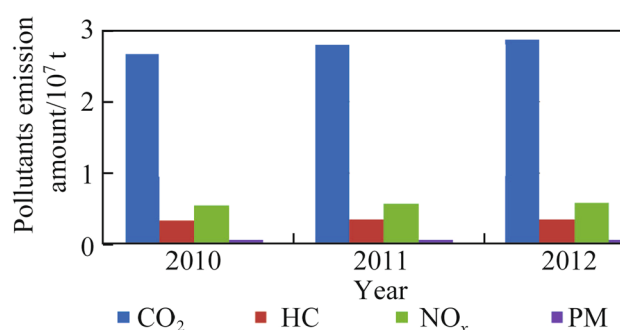


Fig. 3 Changing trends of pollutants emission by China automobiles (Source: “2013 Annual Report on Prevention and Treatment of Motor Vehicle Pollution in China” by the Ministry of Environmental Protection)

had increased from 0.57×10^6 t to 0.59×10^6 t at an average annual growth rate of 2.4%.

With respect to pollutants emission by automobiles in 2012, the total emissions of CO_2 , HC, NO_x and PM by trucks which made up only 17.5% of total holdings of automobiles (while also constituting 87.5% of the total commercial vehicle fleet) were 1.03×10^7 t, 1.47×10^6 t, 3.94×10^6 t, 0.47×10^6 t, respectively. Accordingly they represented 35.8%, 42.6%, 67.5% and 78.6% of the total CO_2 , HC, NO_x and PM emissions, respectively.

2.4 Future prospects of China commercial vehicles

Although the automobile fleet in China has been growing with the increase in production and sales of automobiles, in 2012, the per capita ratio in this regard was only 79 vehicles per 1 000 persons, which is nearly half of the average level of the world. This level was far lower than that in developed countries (500–800 vehicles per 1 000 persons). It is quite conceivable that the Chinese automotive market, despite already being the largest in the world, continues to have enormous growth potential.

According to a relevant forecast [5], by 2020 and 2030 the total fleet of automobiles in China will respectively

reach 250–290 million and 400–520 million. The growth rate for passenger vehicles is relatively fast and there exists some uncertainty. Passenger vehicles will reach 220–260 million and 350–480 million by 2020 and 2030, respectively, while the commercial vehicle fleet will grow to 33 million and 47 million, respectively.

Based on the above forecast it is safe to say that China's automotive products, in particular commercial vehicles, will bring severe pressure on the energy supply security and environmental-protection efforts. Therefore it is very important to adopt appropriate measures to achieve fuel-saving and emission-reduction by raising future technological level of commercial vehicles.

3 Main emission-reduction measures relating to the automotive industry

In recent years China's government, automotive industry and enterprises have been taking active steps to promote fuel-saving and emission-reduction.

For example, the Chinese government has issued a series of plans, policies and regulations to drive development of energy-saving and alternative-energy vehicles [6]. For example, "Development Plan for Energy-Saving and Alternative-Energy Vehicles (2012–2020)" (issued in 2012), "Twelfth Five-Year Plan Period on 'Energy Development'" (issued in 2013), "Action Plan for Preventing and Treating Atmospheric Pollution" (issued in 2013), "Energy Development Strategic Action Plan (2014–2020)" (issued in 2014 by the State Council), "Notice on Management of Fuel Consumption of Heavy Duty Commercial Vehicles" (jointly issued in 2012 by MIIT and Ministry of Communications), "Strengthening Coordination on 'Vehicles, Petrol and Road' and Expediting Proposal for Prevention and Treatment of Automobile Pollution" (jointly issued in October 2014 by CDRC, Ministry of Environmental Protection, MOST and MIIT, etc.), and a series of emission control standards were implemented over various stages (namely National Standard 1–5, etc.).

There also have been active initiatives by relevant organizations in the automotive industry. They exert their efforts through the establishment of technical development and technical exchange platforms as well as formulation of standards, etc. For example, the Society of Automotive Engineers of China (SAE-China) has played a leading role in the establishment of China Auto Lightweight Technology Innovation Strategic Alliance, Strategic Alliance for Innovation Electric Vehicle Industry and Strategic Alliance for Innovation in Telemetric Industry, as well as Technical Forum for China Automotive Lightweight and Conference on China Automotive Lightweight, etc. They

have also formulated numerous technical specifications for alternative-energy vehicles and automotive lightweighting, along with the publication of numerous books covering this topic.

With the government support and active efforts by the industry, both car manufacturers and spare part enterprises have also taken active steps such as adjustments in their strategic planning, establishment of specialized branch companies (for examples the alternative-energy vehicle branch of the car companies) and increased investments in relevant research and development, in order to drive fuel-saving and emission-reduction.

In a word, Chinese government, the industry and enterprises are making great efforts in providing favorable conditions for the development of fuel-saving and alternative-energy vehicles. They also provide strong impetus to continuous improvement in new-energy vehicle technology, IT-enablement technology and lightweight technology.

4 Lightweighting as an effective way to fuel-saving and emission-reduction for Chinese commercial vehicles

Lightweighting is feasible under the conditions of cost control and performance improvement. Weight reduction can be achieved through lightweight design and technologies for integrated application, materials and advanced manufacturing [7]. Reduced weight for automobiles can significantly reduce fuel consumption and emissions. In a strategic forum on body engineering held in Germany, organized by Automotive Circle International in 2011, Fiat drew a conclusion after a comprehensive analysis: for every 10% reduction of a motor vehicle's weight, the fuel consumption can be reduced by 3.5%–6%. Furthermore, there are differences in the relationship between the weight of an automobile and its fuel consumption under different road conditions. Thus, under certain conditions fuel consumption can be reduced by as much as 8%. Correspondingly, the emission of carbon dioxide will be proportionately reduced, while the emission of other hazardous substances will be reduced by 5%–6%.

Overall, Chinese commercial vehicles are on average 10% heavier than similar-class foreign vehicles and key components such as vehicle frames and suspension springs are even heavier by 30%–40% [8]. The analysis results made by China Auto Lightweight Technology Innovation Strategic Alliance with respect to weight-reduction for Chinese heavy-duty trucks and tractors by using trailer/tractor ratio are showed as follows.

The coefficient of payload utilization is the ratio of a motor vehicle's payload mass to its tare mass, which can reflect the level of light-weighting of trucks and dumpers.

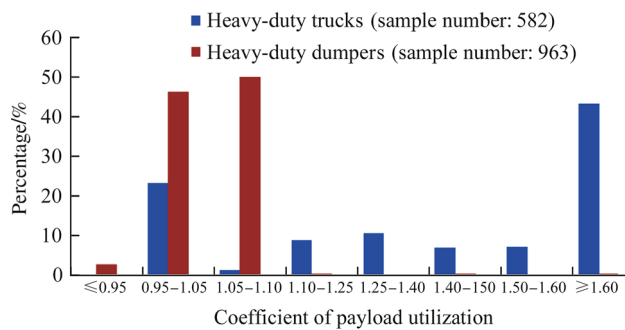


Fig. 4 Coefficient of payload utilization of Chinese trucks and dumpers (Source: Rearranged based on 226–229 public notices by China Auto Lightweight Technology Innovation Strategic Alliance in its “Automotive Manufacturers and Products” report)

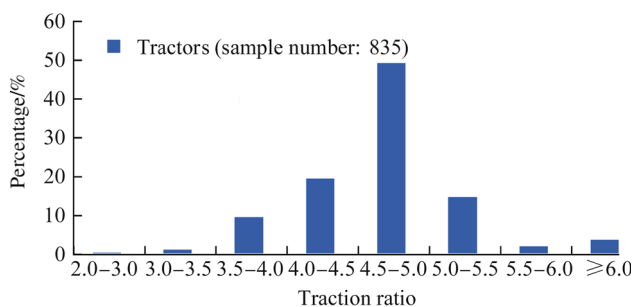


Fig. 5 Traction ratio of China tractors (Source: Rearranged based on 226–229 public notices by China Auto Lightweight Technology Innovation Strategic Alliance in its “Automotive Manufacturers and Products” report)

For trucks and dumpers with similar tare mass (tonnage), the greater coefficient of payload utilization would imply the higher level of automobiles’ light-weighting, since they would be able to carry more cargos. By statistically analyzing 582 heavy-duty trucks and 963 heavy-duty dumpers based on 226–229 public notices in “Automotive Manufacturers and Products”, it was found that over 96% of Chinese dumpers produced by indigenous brands had a coefficient of payload utilization of 0.95–1.1, while only 43% of Chinese trucks had a coefficient of payload utilization exceeding 1.6 (see Fig. 4). In contrast, trucks and dumpers of foreign brands all had coefficients of payload utilization exceeding 1.6. In some cases it was as high as 1.75 (such as in the case of GAC Hino).

The traction ratio is the ratio of tractor’s total mass and tare mass. It can reflect the level of tractors’ light-weighting. For tractors with similar tare mass (tonnage), the bigger the traction ratio is, the more payloads the tractor could carry and a higher level of light-weighting the tractor has. By statistically analyzing 835 tractor models based on 226–229 public notices in “Automotive Manufacturers and Products”, it was found that only 20%

of Chinese indigenous heavy-duty tractors have a traction ratio exceeding 5.0 (see Fig. 5). In contrast, most tractors of foreign brands have a traction ratio above 5.2, some even reaching 6.93 (such as Mercedes Actros).

Based on the aforementioned analysis, there is great potential of lightweighting with respect to heavy-duty trucks, dumpers and tractors, which would be an effective means for fuel-saving and emission-reduction of Chinese commercial vehicles.

5 Conclusions

- (i) China’s automotive sales and fleet will continue to grow, but China’s automotive industry must take into consideration the aspects of fuel-saving and emission reduction.
- (ii) Although commercial vehicles make up only about 20% of the total automotive fleet in China, they significantly contribute to fuel consumption and emission of pollutants.
- (iii) In recent years Chinese government, automotive industry and companies have been taking active steps to promote fuel-saving and alternative-energy vehicles. The government has issued a series of energy-saving and emission-reduction policies to create a more favorable environment for automotive industries, which has helped the development of alternative-energy and lightweighting technologies of automobiles.
- (iv) Compared with the foreign commercial vehicles, Chinese commercial vehicles still have great potential for lightweighting, which would be an effective means for energy-saving and emission-reduction.

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