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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 150mm × 465mm 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.

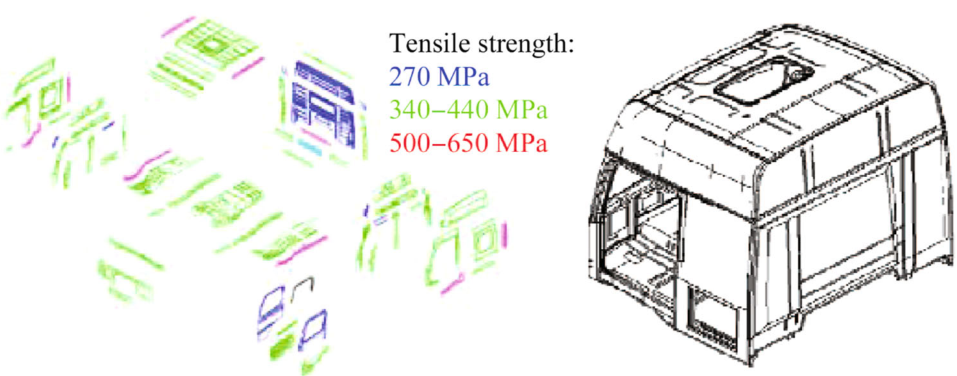

Fig. 6 Application of higher strength steel grades in press stamped components for the truck cabin

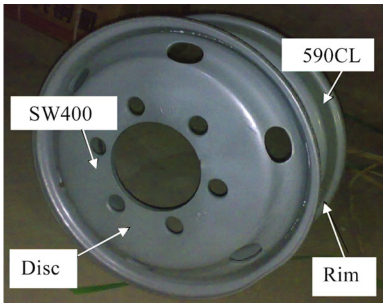

Fig.7 Truck wheel using high strength steel for rim and disc

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

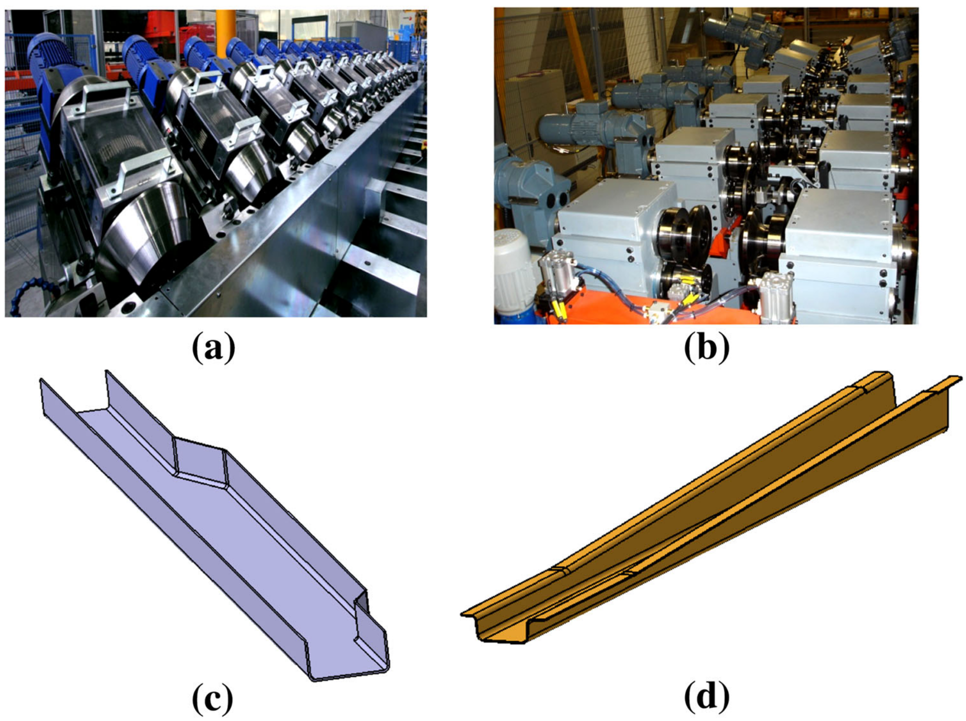

Fig. 10 Equipment for 3D roll forming at Gestamp and possible part shapes with geometrical variation in width (**a**, **b**) and depth (**c**, **d**) directions

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.

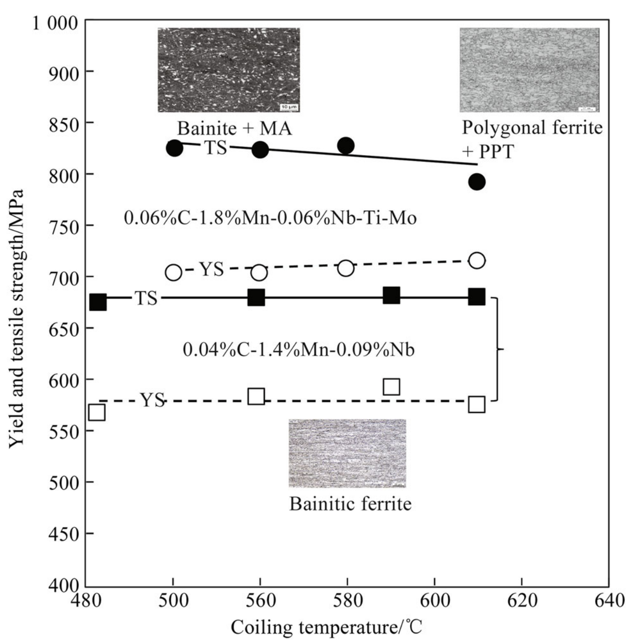

Fig. 11 Robust low-carbon concepts of extra-high strength steels and influence of coiling temperature on strength variation

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

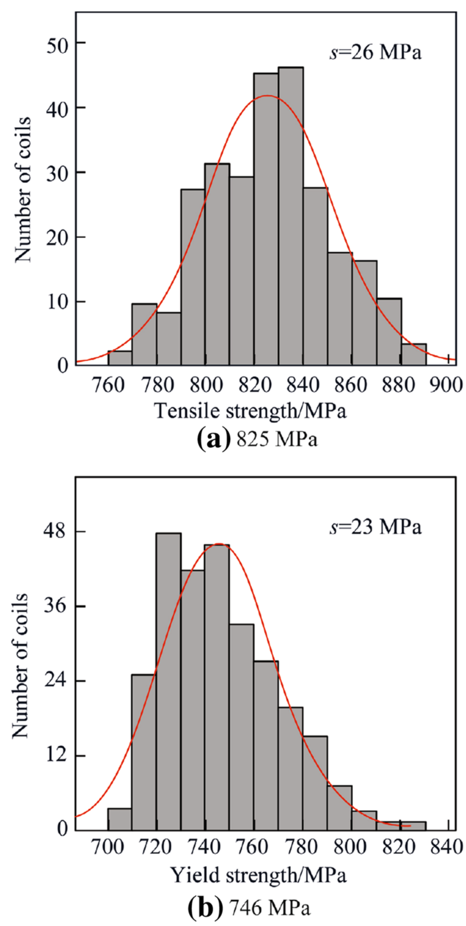

Fig. 12 Narrow strength variation in extra-high strength grade SQ700MCD produced by Shougang

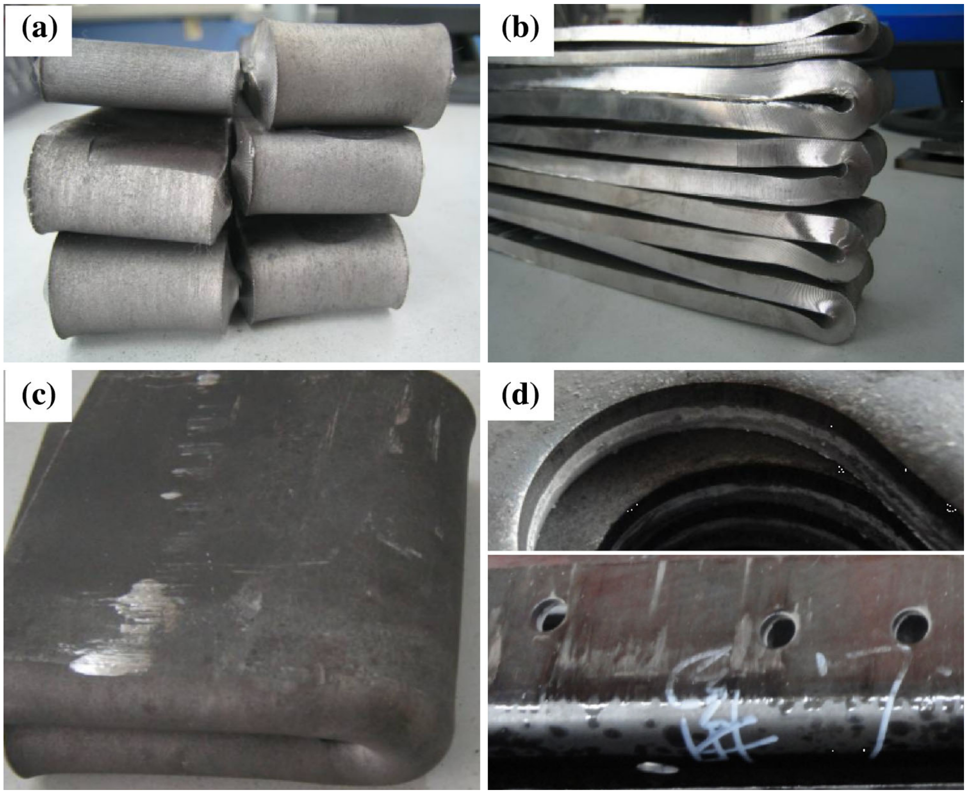

Fig. 13 Bendability of hot rolled strip with 700 MPa yield strength (courtesy Ma steel)

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

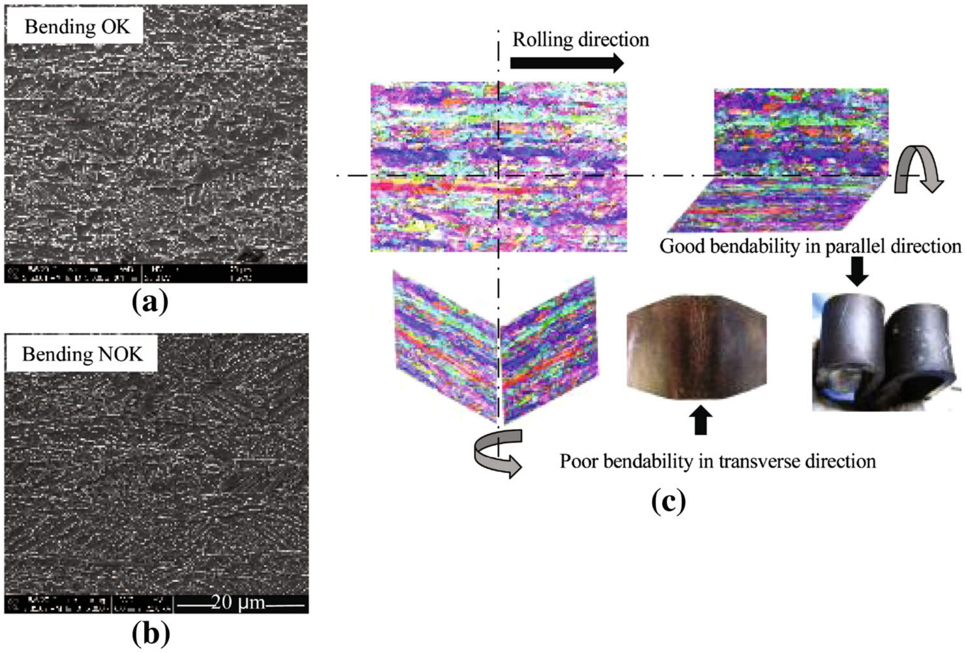

Fig. 14 Microstructural features of DQ steel by SEM (**a**), EBSD (**b**) and influence on bendability (**c**)

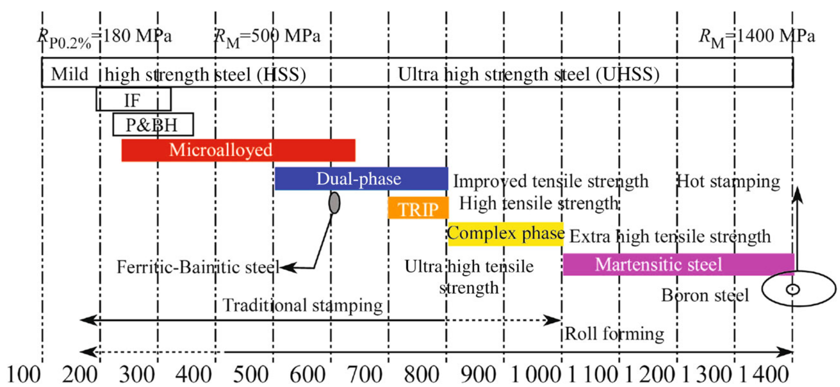

Fig. 15 Automotive steel grades and typical forming techniques as a function of strength

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 intend 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.

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

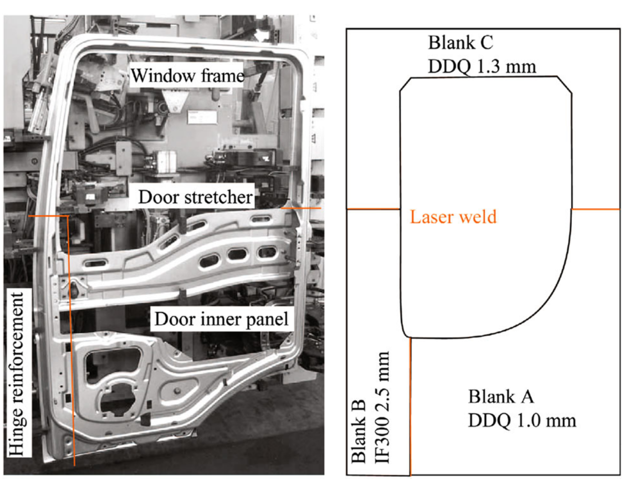

Fig. 16 Tailor-welded blank designed for a truck cabin door optimizing function, weight and material utilization

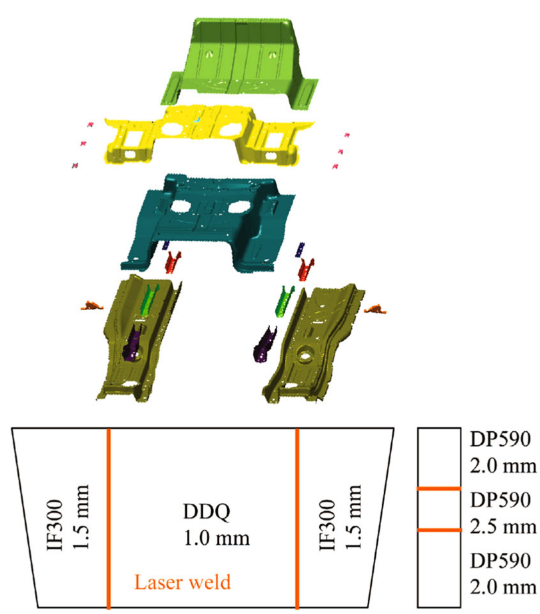

Fig. 17 Tailor-welded blank designed for a truck cabin floor assembly with high degree of part reduction

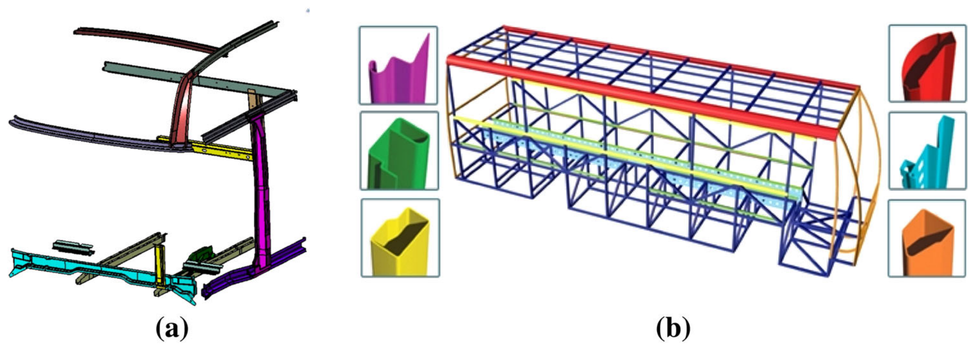

Fig. 18 Profile-intensive designs for truck cabin (**a**) and bus body using open and closed profiles (**b**)

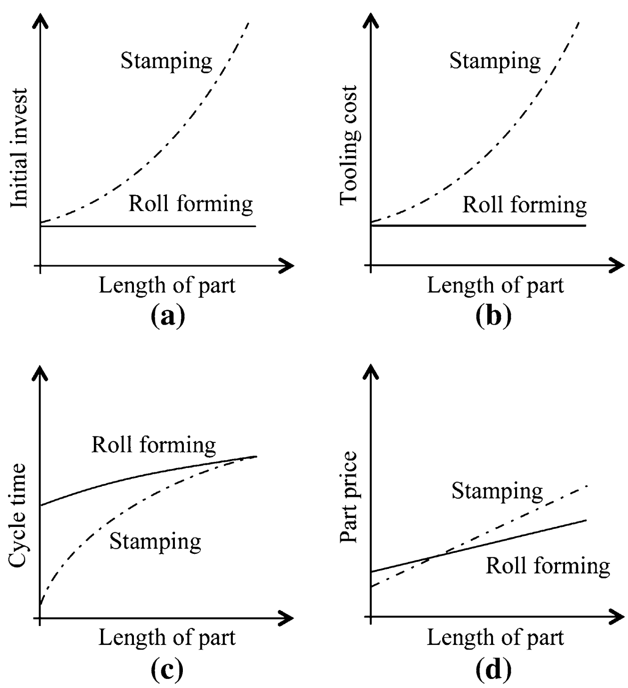

Fig.19 Principle economical comparison between roll forming and press stamping

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

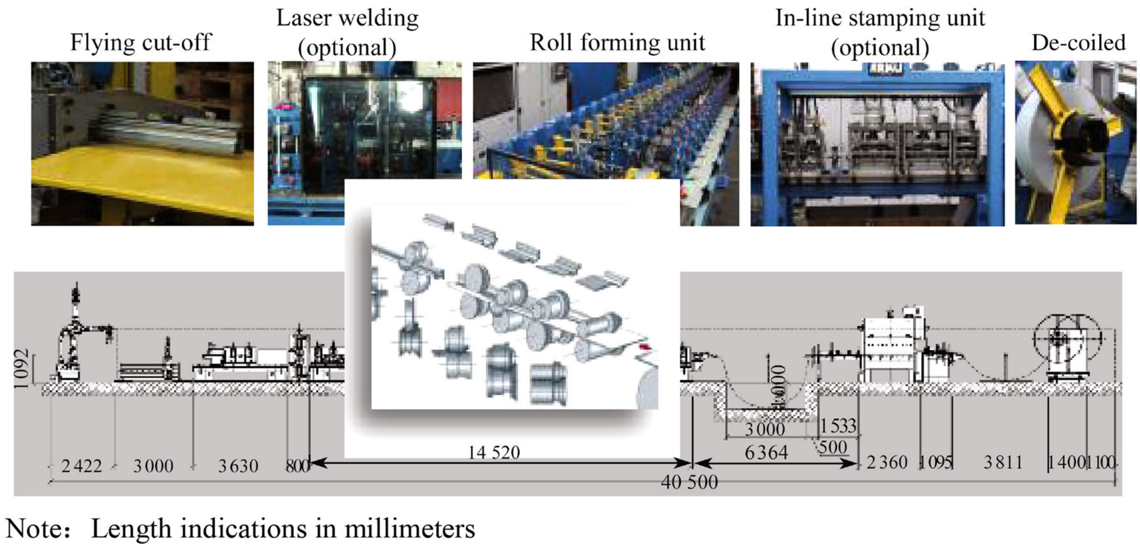

Fig. 20 Configuration of a medium-sized roll-forming line and principle of the profiling process

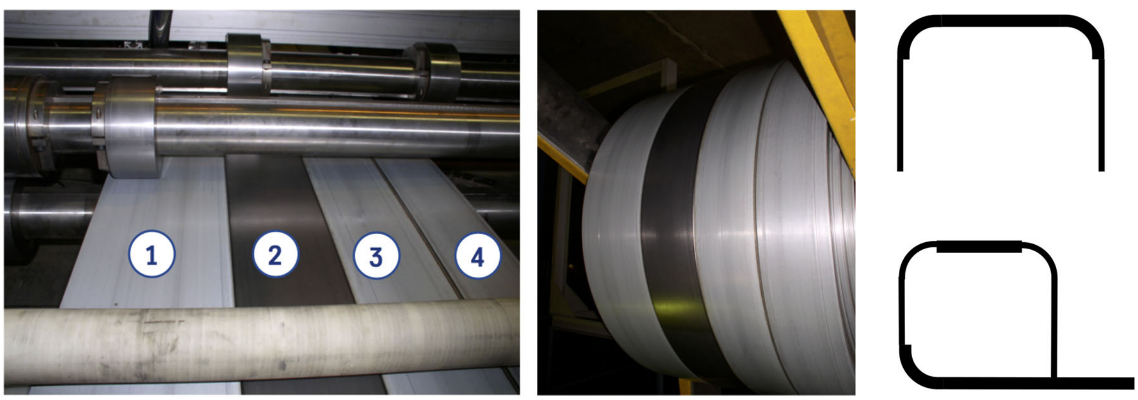

Fig. 21 Example of tailor-welded coil consisting of 4 slit coils and examples of possible multi-gage profiles by roll forming

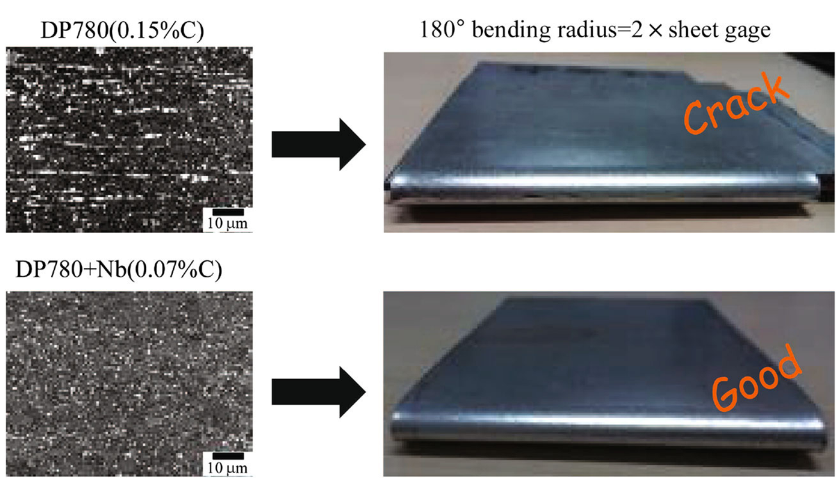

Fig. 22 Microstructural optimization of DP780 steel (Nb microalloying and lowering of carbon content) and resulting improvement of bendability (courtesy Shougang)

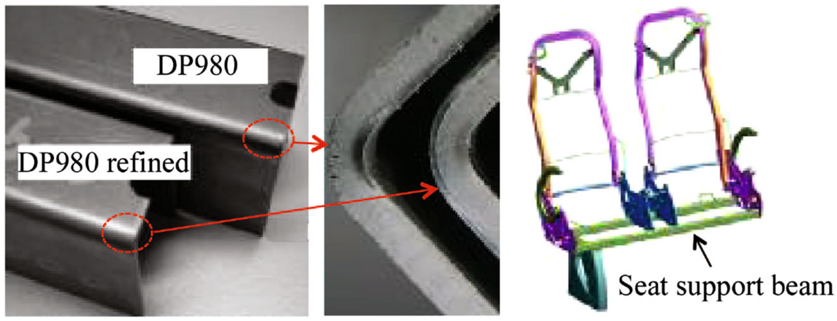

Fig. 23 Roll formed profiles of DP980 steel and appearance of corner cracking with non-optimized microstructure; application example for bus seat support beams

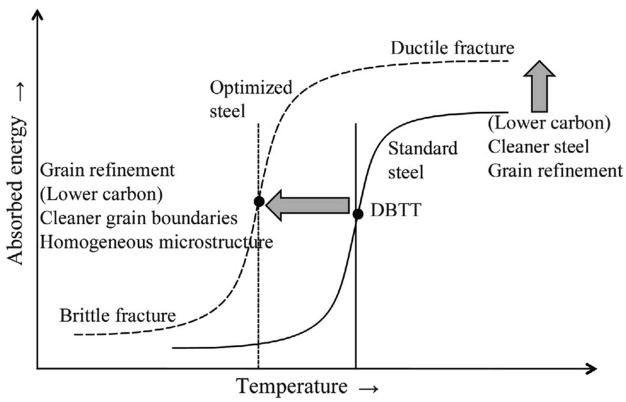

Fig. 24 Metallurgical means of improving toughness behavior in press hardening steel

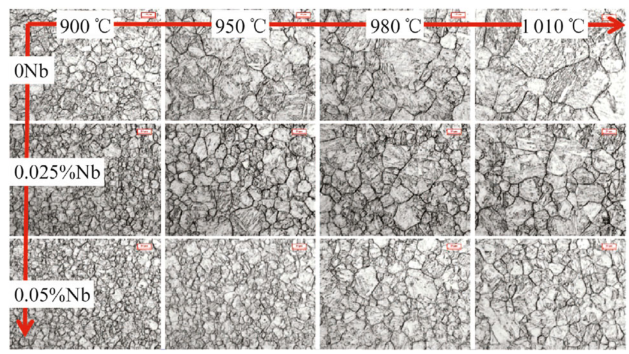

Fig. 25 Influence of niobium microalloying on effective grain size for different reheating temperatures (alloy base: 22MnB5)

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 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.

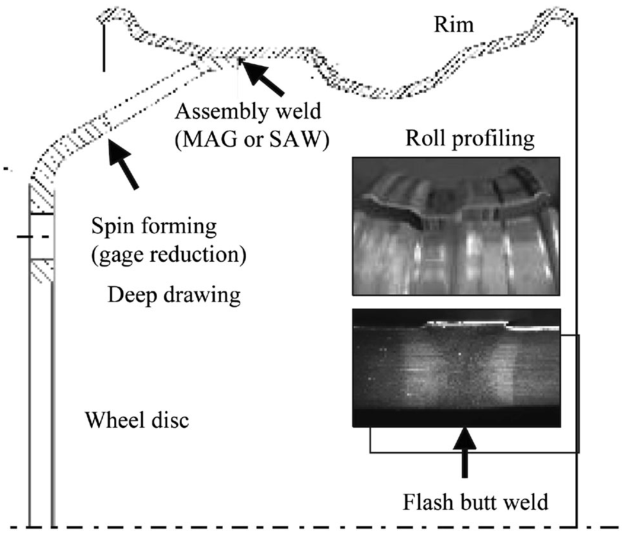

Fig. 26 Typical truck wheel design and involved key manufacturing processes

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

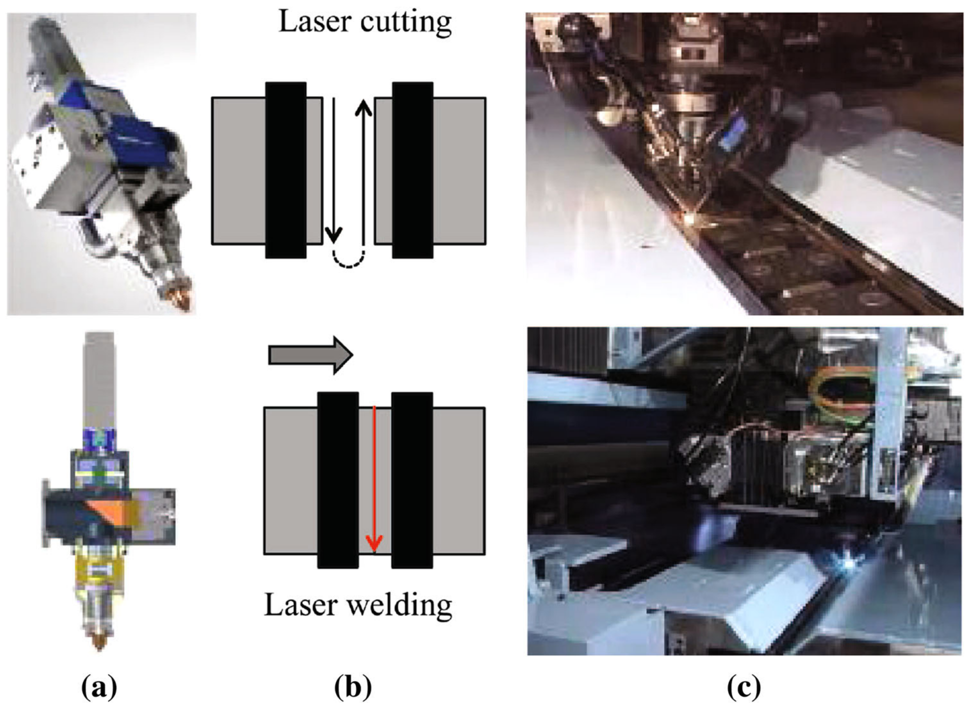

Fig. 27 Principle for laser-based wheel rim welding: combined laser cutting & welding head (a) and cutting-welding process sequence (b, c)

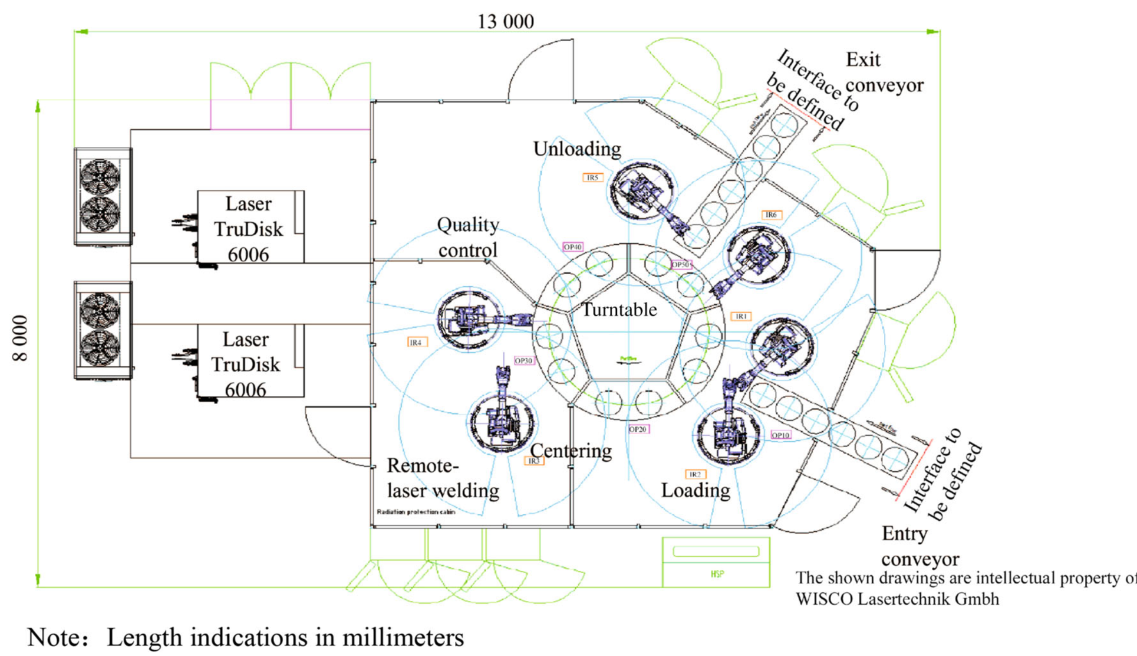

Fig. 28 Concept of a fully automatic stand-alone remote-laser welding cell for assembly welding of wheels

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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