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NEW LIGHTWEIGHT STEELS FOR AUTOMOTIVE APPLICATIONS – POTENTIAL AND RISK

Jürgen Kiese

Volkswagen AG
D-38436 Wolfsburg, Germany

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Abstract

The new lightweight steels, which possess excellent characteristics, are now also of interest to the automobile industry. These steels offer a number of attractive properties (e.g. high strength, high ductility, low density). However, there are some disadvantages, such as the low modulus of elasticity or the high cutting and pressing forces which they require. The higher material costs may limit the usage of these steels in mass-production automotive applications. Nevertheless, the willingness to make use of lightweight steels has increased in recent years.

Introduction

The trend towards higher vehicle weights observed in recent years in automotive engineering is primarily attributable to customers' desire for increased comfort and a level of safety which corresponds to market demands and legal requirements.

The climatic protection conference held in Kyoto focused on the problem of CO_2 and resulted in the adoption of a voluntary commitment to comply on the part of the automobile industry. In comparison with 1990 values, mean fuel consumption must be reduced by 25% by the year 2005. Likewise, the ACEA has also promised to reduce mean CO_2 emissions to 140 g/km by the year 2008. Also, fuel price increases must not be overlooked. Due to increasing environmental obligations and the uncertain global political situation, soaring prices are predicted.

These driving forces are the fundamental considerations supporting lightweight design in the automotive industry. In order to achieve this objective, all lightweight design technologies must be examined, such as lightweight shape, material and structural design. As a result, lightweight material design is now also giving consideration to new, lightweight steels with a high manganese and aluminum content which were not previously used.

Technical Rationale

Modern lightweight steels with a high manganese and/or aluminum content reveal an attractive application spectrum. Their high strength and high ductility make these steels an ideal structural material. Figure 1 shows the mechanical characteristics of these new grades of steel. In comparison with conventional steels, high strength and high ductility, can be combined in one material. Departure from the well-known zone of conventional steels is therefore taking place.

An additional advantage is particularly revealed by steel developments with high aluminum contents. Depending on the composition, density can be reduced down to approx. 6.5 g/cm³.

It should not be overlooked that attempts to achieve such characteristic combinations have already been made in the past with nickel chromium-steels (e.g. Nirosta H400). However, such high chrome and nickel content steels are no longer attractive due to their price. They are only employed if components cannot be implemented using conventional grades of steel.

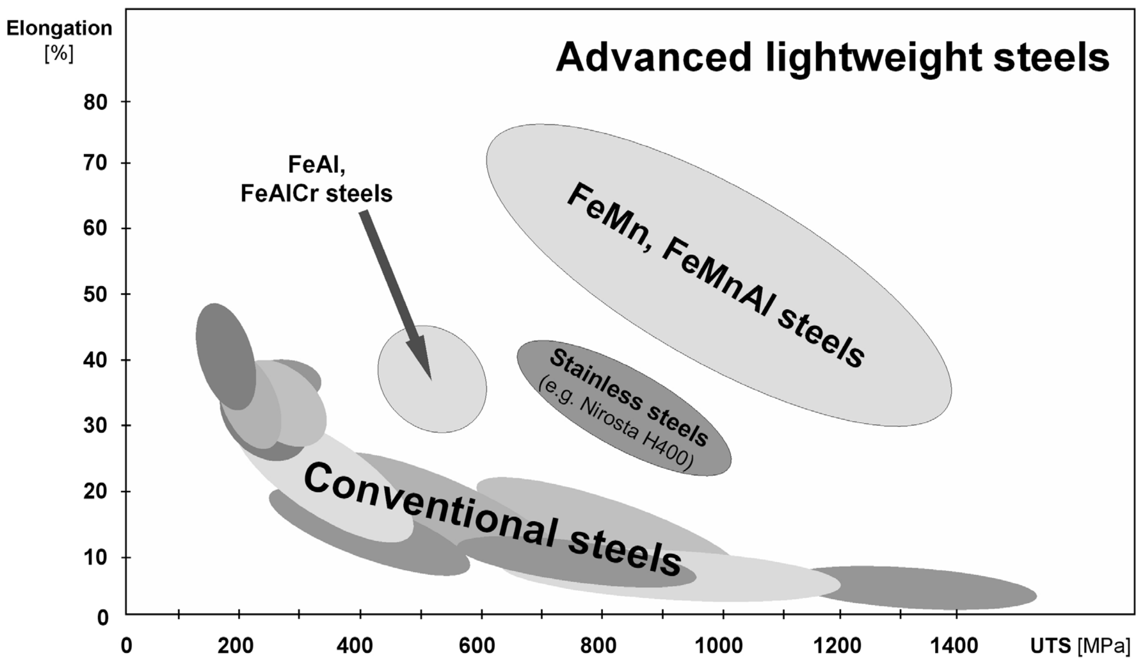

Figure 1. Mechanical properties of modern, lightweight steels

Which Costs are Acceptable?

Modern, lightweight steels reveal manganese contents of up to 30%. Certain developments may also exhibit aluminum contents of up to 10%. Due solely to the composition, it must be clear that these steels will cost more. High aluminum contents, in particular, will make their presence felt. However, one drawback is the higher production costs of FeMn(Al) steels. The addition of high manganese and aluminum alloy contents and further processing of these steels are difficult. Also, some steel producers have developed their own formulations and are unwilling to share the details.

It is perfectly clear that weight reductions cannot be achieved without increased cost, but there are limitations. At present, additional costs for reducing weight by 1 kg in mass production are barely acceptable in the automotive industry. In contrast, slight additional costs are tolerated in small-scale series production or in the premium segment, depending on the vehicle class and the specific overall weight situation. A distinction also has to be made on the location of weight reduction on the front or the rear axle. Generally, acceptance is greater at the front as well as in the upper area of the car.

Statements on material costs are not yet possible as the development of lightweight steels is still evolving. Only test material and preliminary versions of the new grades of steel are available. Perhaps most importantly, in the final analysis, the price will be determined by supply and demand.

As pure substitution material, the new grades of steel will not attain success in automotive engineering. Lightweight steels will only be implemented if they can be used to achieve further advantages. Probably the most obvious advantage is the weight saving possible by reducing thickness as a result of higher strength. Another important, technical advantage is the reduction in weight attainable by exploiting so-called secondary effects. This means that other components or entire component assemblies can be made lighter or produced less expensively by using these new grades of steel. Component integration is the key word in this regard. Table I shows certain important potential applications for lightweight steels. In the end, everything is oriented towards achieving a cost advantage, whereby a technological advantage or pioneering position may play an important role.

Table I. Motivation for and potential usages of modern lightweight steels

Motivation	Potential usage	Comment
Technology	Use in components with a high level of formability	Complex geometries
Lightweight design	Use in strength-relevant components	Reduction of sheet thickness
Safety	Crash-relevant components with high deformation potential	Energy absorption
Cost reduction	Replacement of cost-intensive materials/processes	Stainless steels, aluminum; hot forming

Development Trends

At present, three development trends can be discerned in modern, lightweight steels (Figure 2). These involve steels with high manganese contents, with and without aluminum, and steels containing aluminum. The transitions between these three types of steel are fluid.

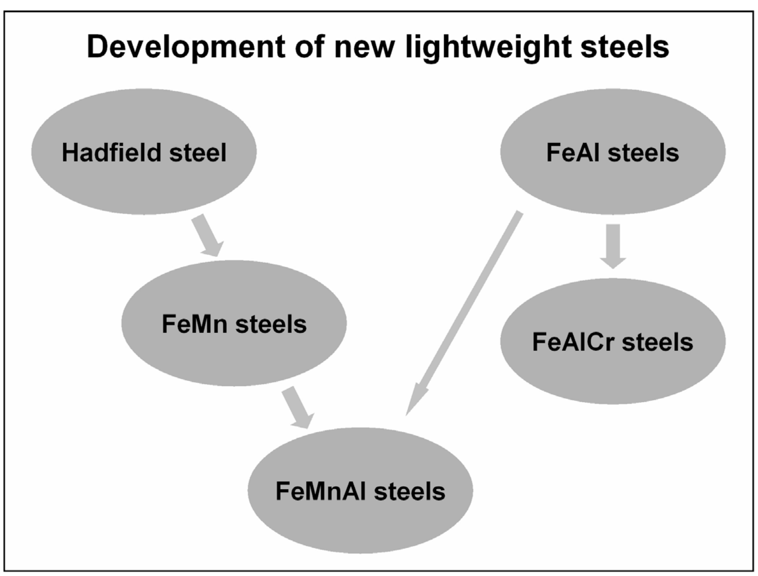

Figure 2. Lightweight steels – development trends

FeMn Steels

The origin of the FeMn steels or steels with high manganese contents is the Hadfield steel X120Mn12, named after its inventor Sir Robert Abbott Hadfield (Table II). The high manganese content (12 - 14%) and the relatively high carbon content (1.2%) stabilize the austenitic phase, and achieves an extremely ductile structure. However, Hadfield steel's application areas include wear-resistant parts, as high hardness values can be attained by means of suitable thermomechanical treatment.

Table II. FeMn and FeAl steels

	$\sigma_{0.2}$ [MPa]	UTS [MPa]	El [%]
X120Mn12 Hadfield steel	380	1000	45
HT700T residual austenite steel (conventional TRIP steel)	450	700	25
Fe-15Mn-3Al-3Si-0.02C modern TRIP steel	350	1050	35
Fe-25Mn-3Al-3Si-0.03C TWIP steel (1st generation)	260	650	80
Fe-23Mn-0.6C TWIP steel (2nd generation)	450	1000	60
Fe-26Mn-11Al-1.1C FeMnAl steel	700	850	65
Fe-6Al-0.05Ti-0.05Nb-0.002B FeAl steel	330	550	35

One of the next steps was to add aluminum and silicon to these steels via alloying and further increase the manganese content [1]. This enables elongations of approximately 35% (Table II). Due to its very high manganese content, however, the TRIP steel specified here differs significantly from the conventional TRIP steels. Conventional TRIP steels, which are also called residual austenite steels, merely reveal manganese contents of around 2% (Table II). Commonly, however, they display what is called the TRIP effect, which occurs in the structure in the event of plastic deformation. TRIP stands for "transformation-induced plasticity" in which elongation-induced martensite is formed.

If the manganese content is significantly increased, e.g. to 25%, a grade of steel that is characterized by even higher ductility is obtained [1]. Elongation at facture approaching 80% is achieved (Table II). The plasticity mechanism has changed, and the TRIP effect no longer occurs. Plasticity-induced twinning arises which is called the TWIP effect (twinning-induced plasticity). Typical compositions in this case are manganese contents of around 25% with 3% aluminum and silicon. These are referred to as 1st generation TWIP steels. However, it has been shown that problems may arise in this 1st TWIP generation during welding (RSW, laser, MAG) if one of the welding partners or the TWIP steel itself has a galvanized surface. Zinc infiltration may occur along the grain boundaries, rendering the joints unusable. However, the TWIP steels have to be galvanized for body applications, as the manganese does not contribute towards corrosion protection. In addition, the aluminum content is too low to protect the TWIP steel against corrosion.

The next FeMn steel development step (2nd TWIP generation) involved omitting the aluminum and silicon alloying elements. This 2nd TWIP generation, e.g. Fe-23Mn-0.6C (Table II), is characterized by very high strength (UTS = 1000 MPa) with very good ductility (El = 60%). The yield strength in this case is 450 MPa, i.e. the steel shows pronounced work hardening (Figure

3). However, two well-known problems, which were previously observed in the case of austenitic and high-strength steels, arose in the 2nd TWIP generation. These are delayed fracture (Figure 4) and certain notching sensitivity (Figures 3 and 5).

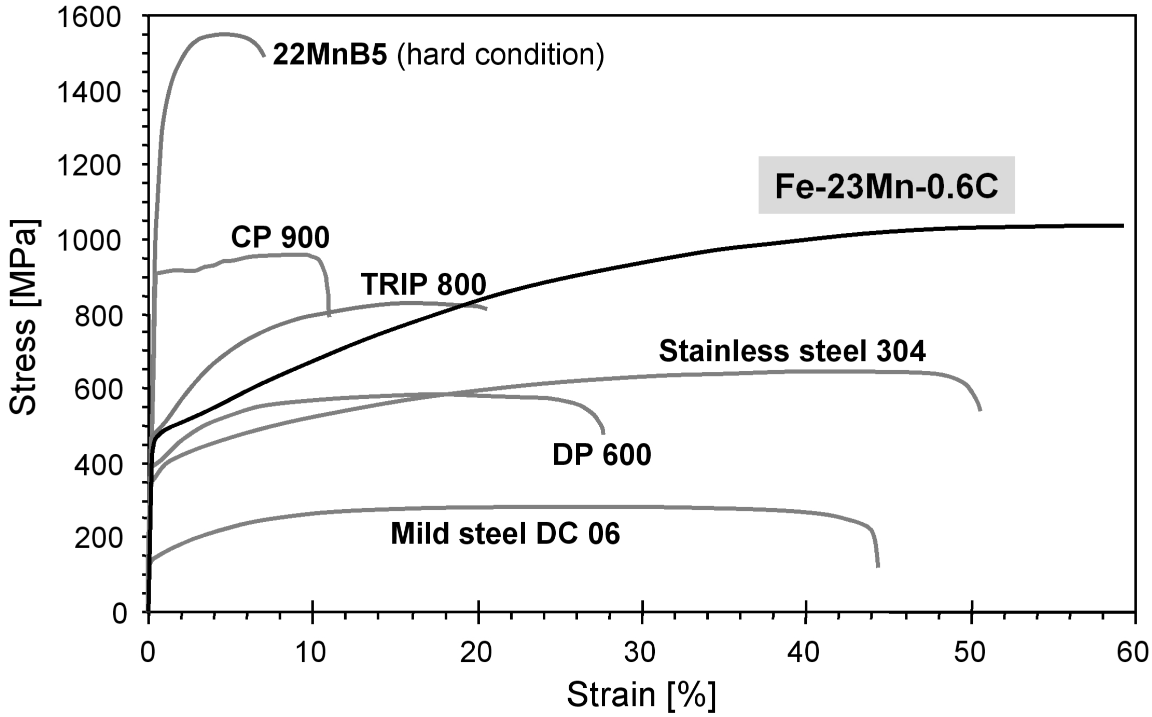

Figure 3. FeMn steel in comparison with conventional automobile steels

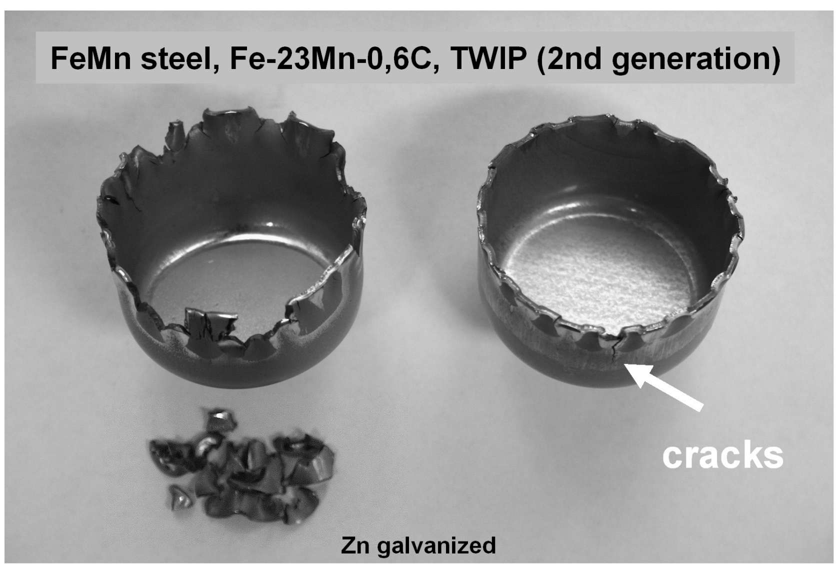

Figure 4. Delayed fracture in FeMn steels (2nd generation)

Due to the high manganese content, the face-centered cubic unit cell of the TWIP steel is significantly expanded, thereby facilitating hydrogen solubility and absorption. Measurements revealed H contents of around 20 ppm, whereby contents of less than 3 ppm are normal. The hydrogen is absorbed during steel production and the galvanization process. The option of releasing the hydrogen by means of heat treatment, via annealing, is still available prior to galvanization. This is no longer possible following galvanization, as the coating is otherwise destroyed. Delayed fracture is primarily a problem in applications in which a galvanized surface is required.

In general, the steel's notching sensitivity increases as strength rises. This problem is extensively prevalent in the 2nd TWIP generation (Figure 5). These FeMn steels fracture without any visible contraction, and are therefore not as damage-tolerant as desired. In tensile testing, preparing the edges of specimens in order to determine the true material behavior is necessary and usual, particularly in the case of high-strength and super high-strength steels. Elongations at break of 60% have been measured in this case. However, variability in edge quality results from trimming in practice and component production. Figure 5 shows tensile tests for the same steel with machined edges. The elongations at break lie between 35 and 45%; the manufacturer's specification is El = 50%, at least. It is therefore sensible to conduct tensile tests with different edge qualities (e.g. stamped, laser cut, etc.), in order to determine sensible values for designing components.

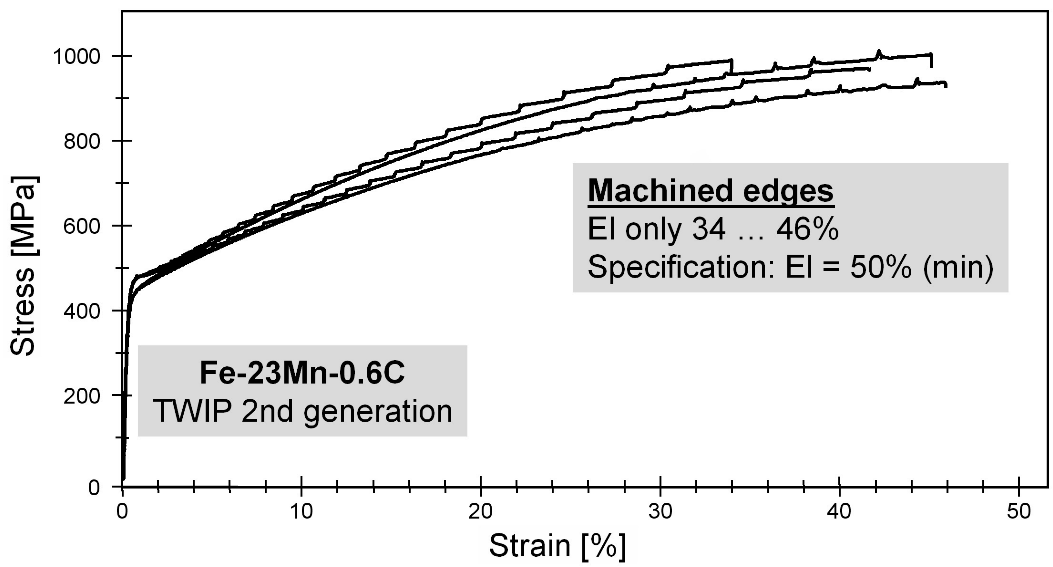

Figure 5. Influence of edge quality on elongation of FeMn steels

A new 3rd generation of TWIP steels is currently being developed by steel manufacturers and institutions. The hydrogen content is said to be significantly reduced, and the hydrogen that is still present within the structure to be bound via purported traps, which are comprised of carbide. Speculation surrounds the composition of the 3rd TWIP steel generation at present, although the carbon content is likely to be slightly higher, again leading to higher strengths.

FeMnAl Steels

One further development within high content manganese steels is a variant, which also has relatively high aluminum (around 10%) and carbon (around 1%) contents (Tab. 2). FeMnAlC alloys were already being dealt with 20 years ago [2]. These grades of steel reveal high strengths (UTS) and high elongations at break similar to those of the above-mentioned TWIP steels. However, their curve characteristics are entirely different [3]. Work hardening is very slight, i.e. they have high yield strengths ($\sigma_{0.2}$), which lie slightly below their tensile strength. As the area under the stress-strain curve reflects the energy conversion capacity, these high content aluminum FeMn steels are pre-destined for components that are intended to absorb energy in the event of a crash. The high aluminum contents enable the achievement of densities of less than 7.0 g/cm³, thereby increasing the lightweight design potential.

These FeMnAl steels do not show either a TRIP or a TWIP effect as their high plasticities are achieved via dislocation slipping forming shear bands, called the SIP effect (shear band induced plasticity). This plasticity mechanism may also possibly be responsible for the fact that these FeMnAl steels reveal contraction prior to fracturing. In addition, the significantly higher aluminum content also leads to anticipation of better corrosion resistance. Dispensing of galvanization may be possible for body applications. Consideration must be given to running gear applications, where non-galvanized grades of steel are generally used. The joining behavior of this grade of steel has not yet been examined to date, but will extensively determine whether use in automobiles is possible.

FeAl Steels

In contrast to the FeMn steels, FeAl steels are fundamentally ferritic, i.e. they possess a body-centered cubic matrix. The aluminum content is usually determined by the application, however, the economics of producing these flat products, particularly sheets, may be cost prohibitive. The limit is likely to be around 6 to 7% (wt.-%), depending, of course, on the other alloying elements [4]. Aluminum contents in excess of 6% lead to the occurrence of the ordered Fe_3Al phase, causing limited forming capacity. Chromium is often added by alloying, in order to increase ductility, particularly at room temperature [5]. Corrosion resistance also increases at the same time. Semi-finished sheet metal products can be manufactured from FeAl steels with relatively low aluminum contents without any problems. In terms of their mechanical characteristics (UTS, El), the FeAl alloys are rather mid-field (Figure 1). Their density depends extensively on their aluminum content. The following rough estimate is that the density is reduced by one percent for each percent of aluminum content.

As the aluminum content increases, chemical, corrosion and scale resistance improve, but also, increased high-temperature strength [6]. The high aluminum content leads to the formation of a surface layer of Al_2O_3, which possesses all of the advantages of a ceramic, whilst the basic material remains ductile. Aluminum contents of 16% (Fe_3Al phase field) additionally result in very low densities of approx. 6.5 g/cm³.

Although these FeAl steels have already been studied in the past, development is only just beginning. Further effort will have to be undertaken for use in automobiles. However, pressure and willingness have increased considerably, as the price of nickel has reached an all-time high.

No Advantages Without Disadvantages

Modern, lightweight steels with high manganese and/or aluminum contents have a significantly lower modulus of elasticity than conventional steels. The modulus of elasticity may decline to 170 GPa, particularly in the case of the FeMnAl alloys. In connection with their high strength, an extensive springback effect arises during forming or deep drawing of these materials. Under specific circumstances, this may prevent certain design geometries, although the material's elongation potential would permit this.

Consideration must also be given to the fact that, when forming these high-strength, high-ductility, lightweight steels, higher pressing forces and therefore new presses may be necessary.

To a certain extent, component integration necessitates even higher pressing forces. However, component integration is necessary to exploit the potential offered by these grades of steel.

High-strength steels, particularly those variants which contain manganese, which are also employed as wear-resistant materials, require higher forces during trimming, which means that cutting tool wear will be significantly higher. Better cutting materials and different processes, such as laser cutting, are required in some cases.

More powerful presses and new laser cutting systems equate to investment and additional operating costs, and are the initial barriers to the use of these modern lightweight steels. In certain cases, however, the advantages will outweigh these challenging factors. Very serious consideration is already being given to applications and potential usages.

High-strength and high-ductility steels vs. hot forming

Hot forming is already an established process in automotive engineering. Both high degrees of forming and high strengths are achieved via hot forming followed by defined, rapid quenching using a relatively inexpensive sheet steel material, 22MnB5. The new Golf V has five components manufactured from hot-formed steel. The most recent, 6th generation of the Passat accommodates nine hot-formed components [7].

In its delivered condition, the initial, ferritic-pearlitic structure of 22MnB5 reveals relatively moderate, characteristic mechanical values ($\sigma_{0.2}$ = 350 MPa, UTS = 550 MPa, El = 25%). In schematic form, Figure 5 shows the changes in properties during the hot forming process.

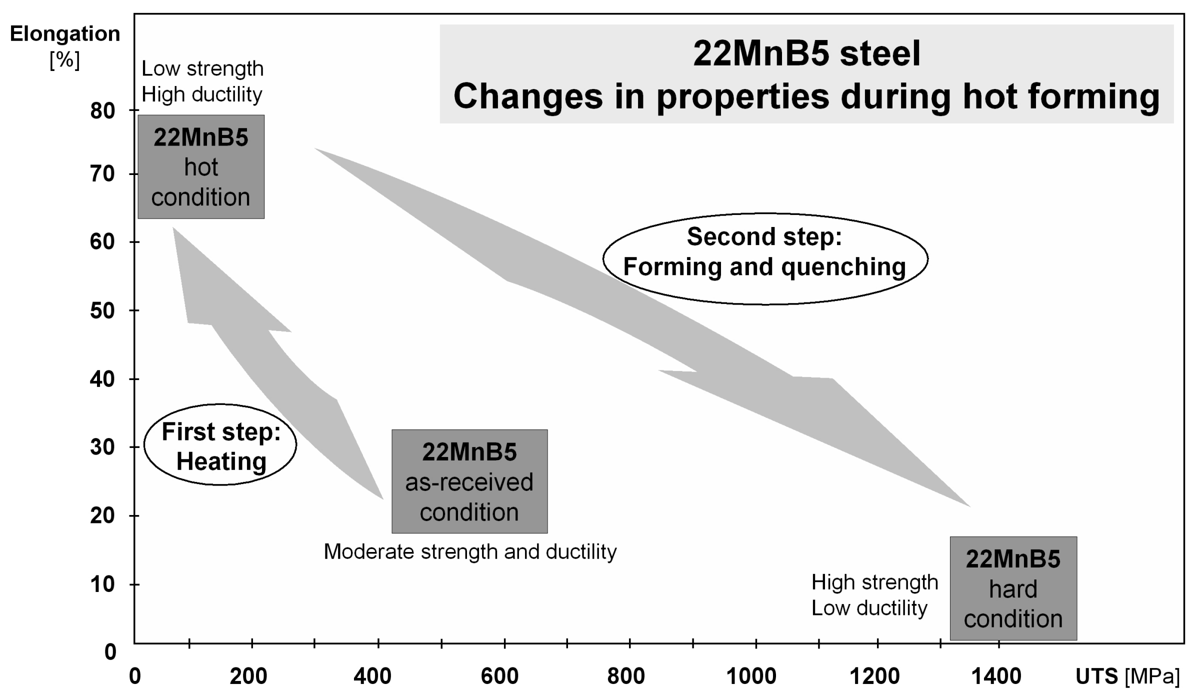

Figure 6. Changes in properties during hot forming of 22MnB5 (schematic)

The trimmed blank used for the component is heated to approx. 950 °C, in which case the material's ductility increases whilst its strength decreases, ideal conditions for forming. The blank is then inserted into the water-cooled pressing die and is immediately formed in one single step. Continuous die cooling gives rise to a martensitic structure with very high strengths in the component ($\sigma_{0.2}$ = 1100 MPa, UTS = 1500 MPa, El = 8%). As practically no springback or elastic recovery occurs on the part of the component, very high component complexity with good forming precision can be achieved using this method. If conventional cold forming takes place prior to this process, it is referred to as an indirect hot forming process.

These advantages face the following disadvantages. Processing galvanized sheets is not possible. Either uncoated 22MnB5 sheets or 22MnB5 sheets coated with AlSi (hot-dip aluminized) are used. If uncoated sheets are used, the oxide layer of scale building up due to annealing at 950 °C must be blasted off. The water-cooled forming dies are expensive, and the hardened components can only be trimmed using a laser. Together with the annealing furnace, this leads to considerable costs, which have to be invested in advance.

Summary

Modern high-strength and high-ductility lightweight steels reveal major potential for usage in automotive applications. Whether they will achieve widespread use will depend significantly on the price of the material and process capability in addition to their technical characteristics. The extent to which these lightweight steels will displace hot-formed sheets additionally remains to be seen. A compromise will also have to be found in this case, with not only selecting the right material, but also the right process in the right location.

References

1. O. Gräßel, G. Frommeyer, Hochfeste TRIP/TWIP-Stähle für crashstabile Fahrzeugstrukturen, Proc. Werkstoffwoche Munich (1999), Vol. II, p. 213- 218.
2. S. C. Tjong, C. S. Wu, The Microstructure and Stress Corrosion Cracking Behaviour of Precipitation-hardened Fe-8.7Al-29.7Mn-1.04C Alloy in 20% NaCl Solution, Material Science and Engineering, 80 (1986) 203-211.
3. U. Brüx, G. Frommeyer, Development and Optimizing of high strength Fe-Mn-Al-C light-weight steels, Presentation, Materialsweek 2004, 7th International Trade Fair for Materials Applications, Surface Technology and Processes in Automotive, Aerospace, Mechanical Engineering, Sports and Consumer Goods, September 21th – 23th, Munich, 2004.
4. U. Brüx, G. Frommeyer, J. Jimenez, Light-Weight Steels based on Iron-Aluminium – Influence of Micro Alloying Elements (B, Ti, Nb) on Microstructures, Textures and Mechanical Properties, Steel research 73 (2002) No. 12.
5. C. G. McKamey, Iron Aluminides in Physical Metallurgy and processing of Intermetallics Compounds, edited by N. S. Stoloff, V. K. Sikka (1996) 351-391.
6. S. C. Deevi, V. K. Sikka, Nickel and iron aluminides: an overview on properties, processing and applications, Intermetallics 4 (1996) 357-375.
7. R. Cordes, M. Norden, The body structure of the new Passat – perfection in light-weight steel and appearance, Steel and automotive body, Symposium, June 16th – 17th, Cannes, 2005.