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Advanced high-strength sheet steels with high manganese contents

High-manganese steels are characterized by high ductility, strength and work hardening resulting from the formation of strain induced martensite (TRIP-effect) or twins (TWIP-effect). A third type is shear band induced plasticity (SIP) in Triplex steels. The Mn-content ranges from 15 to 30 %. Mn and additions of C, Si and Al exert a strong influence on the microstructure and the deformation mechanism and can accordingly affect both strength and ductility. The max. carbon content can be around 1.2 %. The main interest is currently concentrating on TWIP steels. Production of these grades via the conventional steelmaking routes can raise problems and, therefore, modifications and/or alternative production methods have to be applied. With respect to their extreme strength levels, high-Mn steels exhibit an extraordinary forming potential. Welding involves some specific challenges. The possible occurrence of delayed fracture is discussed. High-Mn steels have to compete with other lower alloy steels and special stainless grades with the same objective targets. Referring to this, the laboratory and industrial trials are to be continued in order to fully exploit the considerable market potential of the new steels.

For modern cars, the high crash standards, the demand for weight reduction due to environmental issues, and the highly sophisticated manufacturing processes require strong materials with an outstanding formability. Therefore, the interest in steels showing a superior combination of strength and ductility is very high.

It has been a long time since in 1882, English metallurgist Sir Robert Abbott Hadfield discovered a manganese alloyed steel containing about 1.2 % C and 13 % Mn [1]. This steel possesses both high strength and high work hardening capacity. Hadfield steel became very important in some technical areas where abrasion and impact resistance are particularly demanded. Only three years later, in 1885, the German mechanical engineer Karl Benz designed and built the world's first practical automobile powered by a combustion engine. Since then, a tremendous progress has taken place in car making also having brought about enormous material developments. But as far as ideas on high-Mn steels for the car industry are concerned, they had not been envisaged before the 1960s, but have found stronger interest only since the 1990s. Over the last twelve years, a considerable worldwide increase of activities has been noted in industry and research institutes, whereby the numerous contributions of G. Frommeyer and of B. C. De Cooman should be underlined.

The following report gives an overview of the issues, milestones, and the current state of development in the field of high manganese steels.

The driving force of this material development is the new design concepts for the construction of advanced lightweight and high performance transportation systems, which require the use of high strength and ductility steels combined with enhanced energy absorption.

Physical metallurgical aspects

According to the microstructural deformation mechanisms, **fig. 1**, the group of high-Mn steels can be divided in:

- TRIP effect: transformation induced plasticity via multiple martensitic transformations ($\gamma > \varepsilon > \alpha$),
- TWIP effect: twinning induced plasticity, and
- SIP effect: shear band induced plasticity via severe shear band formation.

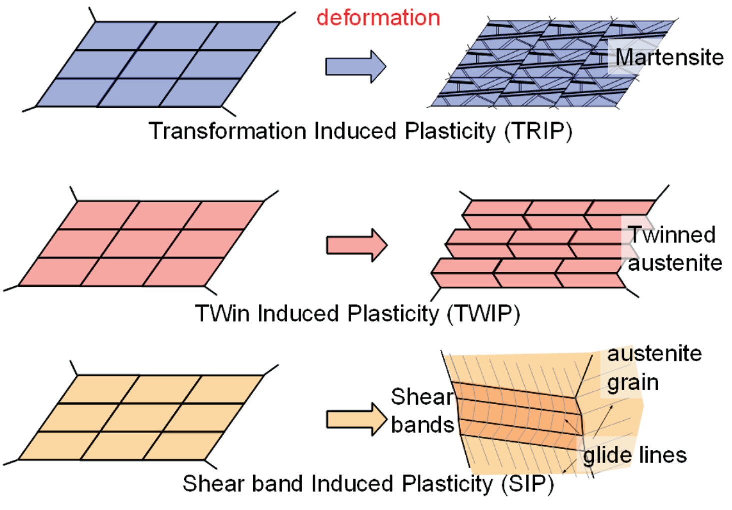


Fig. 1: Different types of plasticity induced by deformation due to microstructural changes

Partial systems have to be considered, because a complete phase system for complex Fe-Mn alloys including the most common alloying elements Fe, Mn, Al, Si and C is not available. The most important binary system Fe-Mn, which has been presented by H. Schumann as a martensitic transformation diagram [2], shows three coexisting phases γ, α, and ε around a mass content of 10 % Mn, **fig. 2.** At lower Mn mass contents, transformation of γ to α takes place, while at higher mass contents transformation of γ to ε occurs. The multiple $\gamma > \varepsilon > \alpha$ martensitic transformation is characteristic for unstable TRIP steels. At Mn mass contents higher than 20 %, the γ phase is very stable, which is characteristic for TWIP steels. In this stringently binary system, however, effects of additional alloying elements on phase stability cannot be seen.

By adding aluminium, the α-region is enlarged at the expense of the γ-region [3].

The ternary system with Si instead of Al looks very similar [4] demonstrating that Si resembles Al concerning phase stability, **fig. 3**.

The austenite is quite efficiently stabilized by increased amounts of dissolved carbon. This effect is used in the 18Mn-0.6C TWIP steels in contrast to low carbon TWIP steels with Mn mass contents of more than 20 %.

The ternary Fe-C-Mn phase diagram, **fig. 4,** does not only show the strong influence of carbon, but also demonstrates the influence of deformation [5], which is stronger for the γ to ε than for the γ to α transformation. In low-carbon grades (around 0.05 %C), transformation to ε-martensite is possible up to Mn mass contents of 27 %. The fully austenitic microstructure is only achieved for Mn mass contents above this level. Plastic deformation even shifts this threshold value to 33 % Mn. Increasing the carbon mass content to, e.g., 0.8 % decreases the threshold value for deformation induced ε-martensite formation to the pronouncedly lower level of 17 % Mn. This finding is most relevant for the design of actual TWIP steels. Once again it has to be underlined that this ternary phase system does not take into account the effects of further alloying elements.

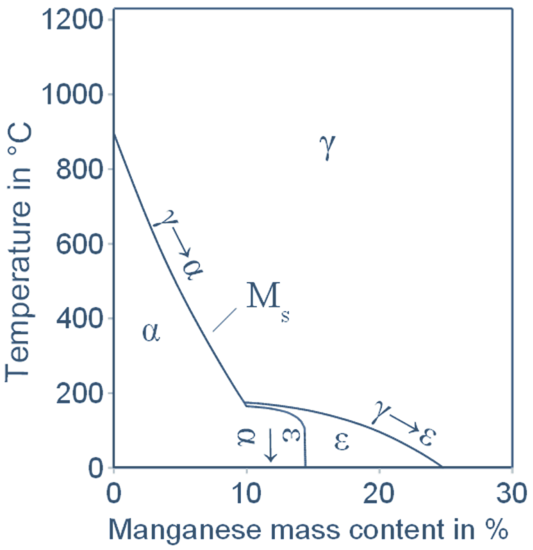


Fig. 2: Iron-manganese binary phase diagram [2]

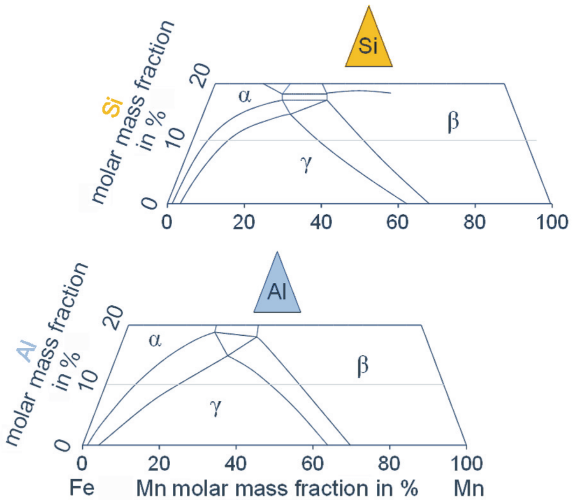


Fig. 3: Sections through the ternary diagrams Fe-Mn-Al and Fe-Mn-Si at 800 °C [4]

When twins form instead of martensite, the strong relation to stacking fault energy SFE must be considered [6]. High stacking fault energies lead to twinned microstructures, while low stacking fault energies generate ε-phase which transforms to α-martensite [7; 8]. Whilst Si-additions to alloys containing £ 20 % Mn promote the γ ® ε transformation at SFE of lower than 20 mJ/m^2, those with higher Mn mass contents exhibit SFE exceeding 20 mJ/m^2. Additions of Al suppress this transformation and promote deformation twinning [9; 10]. In the initial deformation stage, creation of nano-twins [11] is observed comprising high densities of sessile dislocations within the twins [12], which affect their properties. A strong influence of grain orientation on twinning is found [13]. At high strains, twins are also observed in unfavourably oriented grains.

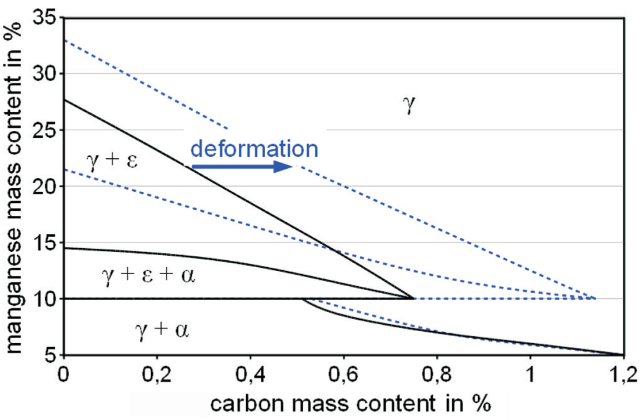


Fig. 4: Microstructure formation in ternary Fe-Mn-C alloys [5]

Fig. 5 shows examples of characteristic microstructures of TRIP, TWIP and triplex steels [52]. Martensite is present as hexagonal ε or as cubic α modification, fig. 5a. Twins are formed by the interaction of inserted stacking faults, shear deformation and gliding of partial dislocations on (111)-planes, fig. 5b. Shear bands (fig. 5c) are formed on (111)-planes and κ-carbides are precipitated coherently to the austenitic matrix.

The existing phases, relations to chemistry and thermodynamic values were taken from [14; 15] and are presented in **fig. 6.** The TRIP effect occurs at relatively low Mn mass contents in accordingly metastable austenite, where the Gibbs free energy ΔG of the austenite to martensite transformation is -220 J/mol for rather low SFE of ≤ 16 mJ/m^2. These factors favour the formation of ε-phase. During deformation, ε-martensite increasingly transforms into α-martensite.

The TWIP mechanism is created at higher Mn contents in accordingly stable austenite, where ΔG is about 110 to 250 J/mol, and the SFE lies in a medium range of arout 25 mJ/m^2. By adjusting the Al content to the Si content in the Fe-25Mn-3Al-3Si alloy, the SFE is defined so that twinning occurs.

The SIP effect is observed in an austenitic triplex steel possessing a relatively high ΔG of 1759 J/mol and high SFE in the range from 110 to 115 mJ/m^2. Extensive homogeneous shear band formation is sustained by a regular distribution of nanosize κ-carbides within the austenite [14; 16].

It is argued that the mechanical properties of TRIP and TWIP steels are solely due to effects related to strain-induced martensite and twinning, respectively. But other mechanisms may also play an essential role, such as, point-defect cluster formation, planar glide, pseudo-twinning and short range ordering [17]. Dynamic strain aging (DSA) in terms of the Portevin Le-Chatelier (PLC) effect may also occur [17...19]. The formation of a C-Mn complex instead of a classical Cottrell effect [19] seems to be responsible for the occurrence of such plastic instabilities. Plastic flow of a TWIP steel showing DSA differs from DSA affected flow of other steels [20].

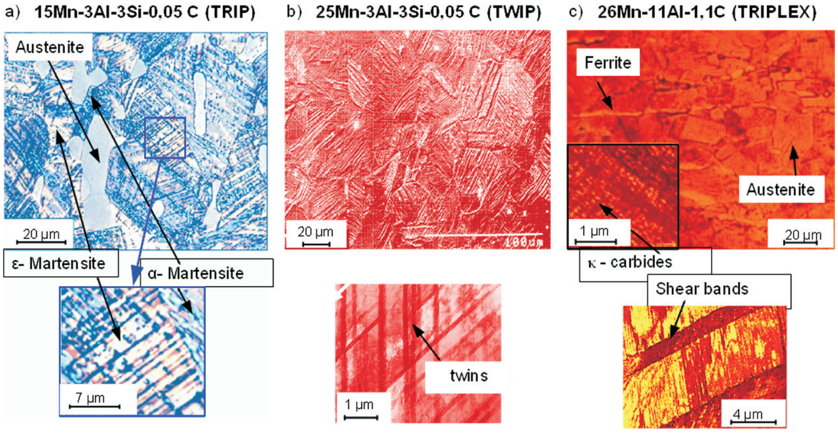
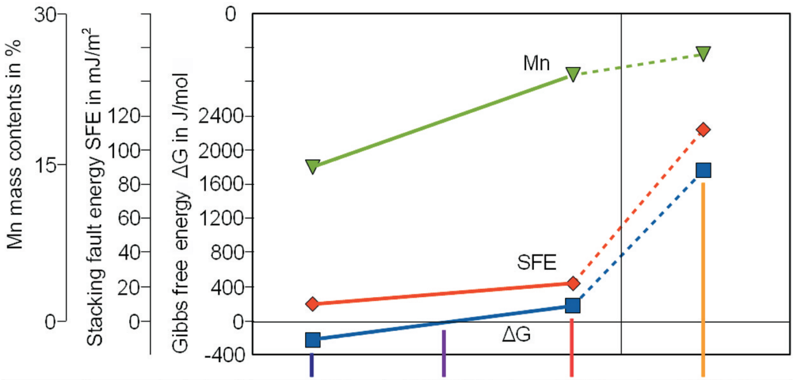


Fig. 5: Microstructure of TRIP, TWIP and triplex steels [52]

Stress-strain relation

Strength-elongation properties. All the different deformation mechanisms lead to high homogeneous elongations at quite high strength values [8]. For low-carbon steels with Mn mass contents of more than 20 %, strength levels of 700 MPa are achieved. Maintaining this Mn level and increasing carbon content to 0.2 % shifts strength to the range between 900 and 1000 MPa, whereas for 0.5 % carbon even 1400 MPa are reached. Therefore, carbon is most important to obtain ultra-high strength. Further, at high strain rates [21], the high manganese steels retain their high ultimate tensile strengths and extremely large elongations.



		strained	m-TRIP	TRIP/TWIP	TWIP	TRIPLEX
alloy			15Mn-3Al/Si	20Mn-3Al-3Si	25Mn-3Al-3Si	26Mn-11Al-1,2C
phases		no	$\gamma + \alpha + \varepsilon$	$\gamma + \varepsilon$	γ	$\gamma + \alpha + \kappa$
		yes	$\gamma + \alpha + \alpha'$	$\gamma + \varepsilon + \alpha'$	γ	$\gamma + \alpha + \kappa$
ΔG	J/mol		-220		110 – 250	1759
SFE	mJ/m²		≤ 16		20 – 25	110 – 115

Fig. 6: Phases and thermodynamic parameters of high-Mn steels [14]

Fig. 7 demonstrates characteristic engineering stress-strain curves of TRIP, TWIP and triplex steels [14]. In the TRIP steels, flow stresses of about 430 MPa, a very high tensile strength of 1130 MPa and a total elongation of about 50 % are achieved. Increasing the carbon content results in a mixed TRIP/TWIP behaviour. The low-carbon TWIP steel shows a moderate flow stress of about 280 MPa, a tensile strength of about 660 MPa and an extraordinary total elongation of about 90 %. A high-carbon TWIP steel exhibits yield stresses of about 410 to 450 MPa and tensile strengths above 850 MPa. Elongation is about 60 %. Triplex steel displays elongations above 50 %, combined with high flow stresses of up to 950 MPa and high tensile strength values of around 1100 MPa.

Strain hardening. Work hardening in *TRIP steels* is primarily due to the formation of martensite. ε-martensite nucleates at stacking faults and α-martensite nucleates in ε-martensite resulting in a multiple martensitic transformation. But initially, at lower strains, hardening is brought about by increasing dislocation density and by an assumed augmentation of stacking faults [22]. As soon as stress-induced α-formation begins, this is quite effective in reducing high local internal stresses within the ε-plates [23]. Work hardening strongly increases due to the following accumulation of α-martensite during deformation. Dynamic strain aging DSA is not observed [19].

In TWIP steels, the course of work hardening is different. At low strain values, hardening is also initiated by increasing dislocation density [19]. It is possible to control the characteristic twinning process by SFE energy through Mn and additions of Al and Si [10; 17]. At lower SFE, the numerous stacking faults impede cross slip to such an extent that planar slip will prevail, causing high strain-hardening rates. Higher SFE promote deformation-induced twins, which gradually reduce the effective grain size in terms of a dynamic Hall-Petch effect. The numerous twin boundaries act as strong barriers to subsequent dislocation motion [24] and contribute to the plastic deformation potential [25]. DSA/PLC was found as additional mechanism [17; 19; 76].

The engineering stress strain curves of the different high-Mn steels presented in fig. 7 were analyzed by the author, resulting in the true stress-true strain curves (fig. 7b) and, finally, the differential strain hardening curves (fig. 7c). The TRIP variant shows the typical behaviour in terms of a strong increase in work hardening at higher strain values due to intensive strain-induced martensite formation. The TWIP grades reveal rather constant work hardening at strain values of more than 0.1. The work hardening of *triplex* steel is comparatively lower for smaller strains around 0.1.

Influence of strain rate and temperature. When the strain rate increases, deformation twins unite together, and deformation twins become denser due to enhanced nucleation [26].

Yield stress increase with strain rate is stronger compared to tensile strength [27]. In contrast to conventional steels, the strain rate sensitivity of high-Mn steels is rather low.

The mechanical behaviour of TWIP steels clearly reveals temperature dependence [28]: At high strain rates the increase in temperature due to adiabatic deformation heating also contributes to SFE.

One additional feature of a high-Mn X-IP steel [29] is its bake-hardening potential which superimposes with work hardening and rises with increasing deformation.

The results of recent investigations [30; 31] on different high-Mn TRIP and TWIP steels confirm the earlier findings concerning microstructures and mechanical properties.

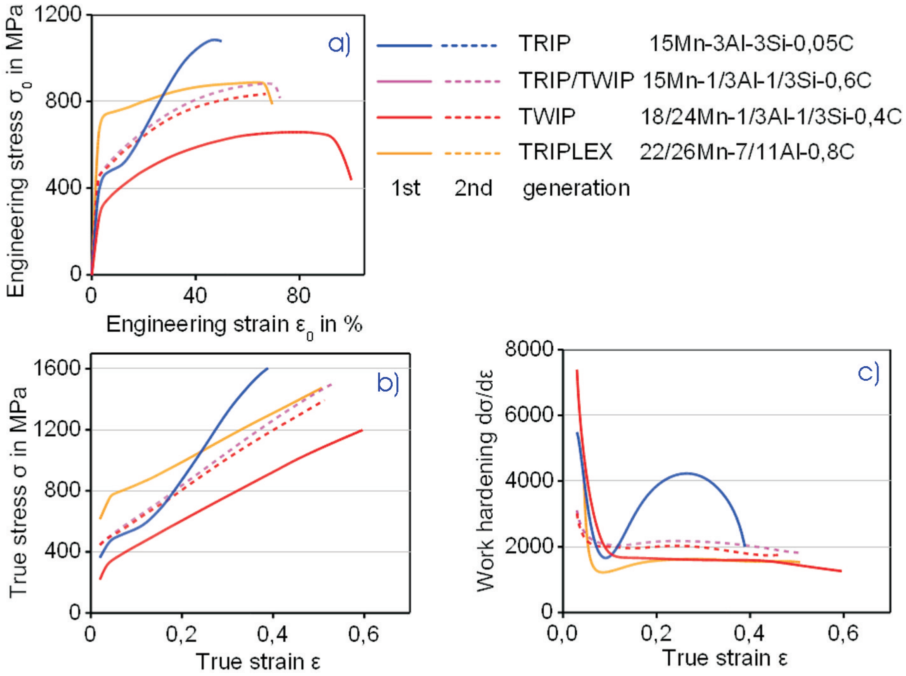


Fig. 7: Strain hardening of TRIP, TWIP and triplex steels [14]

Physical properties

Elastic constants. The shear modulus increases drastically around Néel temperature, above which a material changes its magnetic behaviour [8]. At lower temperatures, a slight increase in shear modulus occurs, whereas above Neel temperature, this modulus decreases with temperature.

The elastic modulus of high-Mn steels is about 10 % less compared with conventional steel grades but, in contrast to the latter, does not show a decrease due to deformation [29].

Density. Density of Fe-Mn-Al steels is remarkably reduced by increasing aluminium contents due to the lower average molar mass content of the alloys and the decrease in the atomic density of the unit cells [14]. Further, manganese in solid solution contributes to the lower density due to its bigger atomic radius.

Corrosion and technological properties

Corrosion. In spite of the comparatively high alloying contents of high-Mn steels, their corrosion resistance is rather low and special means must be applied to protect them against corrosion.

Resistance against red rust could be considerably improved by a thermochemical treatment of C-Mn steel, composed preferentially of 0.6 % C and 20 % Mn. Thus, the steel is recrystallization annealed in a furnace containing reducing atmosphere so that the sheet is covered with an essentially amorphous oxide underlayer (FeMn)O and with an outer layer of crystalline MnO [32]. Moreover, alloying with aluminium seems to improve the corrosion resistance of high-Mn TWIP steels [33].

Forming. In view of the outstanding elongation values of high-Mn steels, a corresponding good forming behaviour is expected. A more thorough assessment of the forming properties is, however, needed due to the ambitious challenges of today´s complex forming procedures.

High strain values of about 75 % were recorded from the circumference of cups [14] leading to the conclusion that both the stretch-forming and the deep-drawing behaviour must be excellent.

With respect to the extreme strength level, X-IP 1000 exhibits an extraordinary forming potential [34], and feasibility was verified for a spectrum of complex automotive components, **fig. 8.** Such ultra-high strength steels show certain characteristics:

♦ distinctive springback behaviour,
♦ comparatively high press forces and
♦ susceptibility to edge cracking during the cutting process.

The latter can be assessed by the hole expansion values, which are rather small compared with low-alloy high-strength steels. An optimization by choosing better conditions or methods for the cutting process is possible.

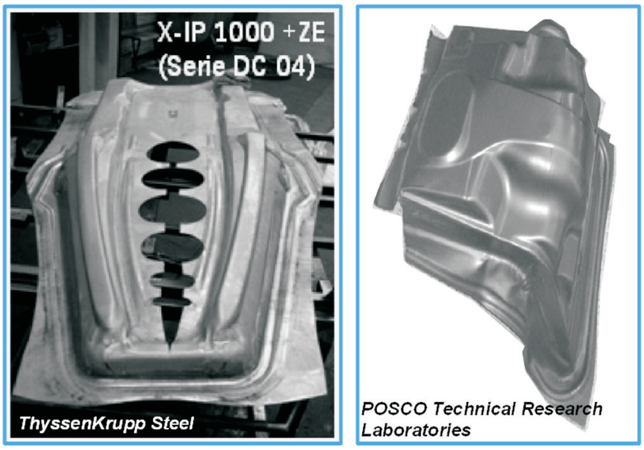
Forming limit diagrams disclose the excellent formability [31]. But in contrast to conventional grades, classical failure evaluation represented by the forming limit curve (FLC) is only applicable with limitations, because ductile shear fracture is the quite dominant failure mechanism [34].

As an alternative to cold sheet forming, a hot forming process has been proposed [35].

Joining. Welding an ultra-high strength steel like X-IP in dissimilar joints involves some specific challenges arising from the different chemical compositions, the different microstructures, and the differing thermophysical properties of the steel grades [34]. Unfavourable thermal physical properties (low thermal conductivity, high thermal expansion, broad melting interval) lead to high distortion and residual stresses [36].

After zinc coating, high-Mn steels may show weld cracks caused by zinc infiltration into grain boundaries [34]. The risk can be diminished by reducing the heat input in combination with the use of optimized wires and advanced welding equipment.

Fatigue. A high-Mn TWIP steel has very good fatigue strength in strain-controlled loading, which is equivalent to or better than that of lower alloyed conventional TRIP 800 [37]. During fatigue of a high-manganese TWIP steel the deformation mode exhibits twinning-induced plasticity [38; 39]. But the twin density in the plastic zone and the resulting hardening both are very low. This provides for more ductility and a crack growth rate lower than with conventional high-strength steels. This result is confirmed insofar as in TWIP steels planar slip bands are formed, but no twins, at an early stage of cyclic straining [40].



Shock absorber housing
(Fe 18Mn 0.6C 1.5Al)

Fig. 8: Feasibility of severe press forming verified for complex parts [34; 76]

Actual high-Mn steels

TRIP, TWIP. The chemical composition of common high-Mn TRIP grades is in the low-alloy range with mass contents of less than 20 % Mn combined with low carbon contents. TWIP steels can be divided into two groups:

- the actually most important one with ~ 0.6 % C and 18 % Mn, and
- one with low carbon contents and Mn mass contents of more than 20 %.

Current TRIP and TWIP steel variants can also contain other elements, first of all Al and Si.

The main interest of current developments is concentrating on TWIP steels. At the beginning of the development of high-Mn steels (Mn > 15 %), one generic steel had preferentially less than 0.7 % C, optional Al and other elements, providing an austenitic microstructure with superior formability and strength by twin formation [41]. This grade already exhibits some essential compositional features characterizing the scope of high manganese steels.

The following development results often refer to compositional features with emphasis on Mn, production methods, properties and application aspects. One example relates to reduced density and combines extreme elongation with ultra-high tensile strength [42]. Another development result is a steel particularly composed for application in the automotive industry [43...45]. It is based on a density-reduced steel revealing TRIP and TWIP properties, presented as lightweight steels with induced plasticity (LIP). Another route aiming at ultra-high strength makes use of a chemical composition including a very high carbon mass content in the range of 0.85 to 1.05 % and one or more elements of Cr, Mo, Ni, Cu, Ti, Nb, V [46]. Other developments also deal with higher carbon grades. A high-Mn TWIP grade is made up of around 0.6 % C, 18 % Mn, 1.5 % Al and optional boron [47]. A similar base composition may contain Ti and/or Nb [48].

As another result of the further development, the austenitic TWIP-type X-IP steel attains ultra-high tensile strength and the yield strength can be varied by different production conditions [34; 49].

Note that elsewhere the high-Mn steels are also named HSD-steels (high strength and ductility) [50].

Triplex. Triplex steel has a generic composition of 18 - 28 % Mn, 9 - 12 % Al, and 0.7 - 1.2 % C [16; 51...53]. The characteristic properties in terms of both high flow and tensile strength combined with high ductility are caused by the SIP effect explained above.

Particularities of the steel making process

Melting. One main concern is manganese alloying. Direct alloying by injection of Mn ore into the melt is very useful to replace Mn-metal alloy [54]. Ferromanganese is also a major source for the introduction of phosphorus into the steel [55]. A selective removal of P is enabled by different mixtures of slags. Measures against Mn slagging and to improve Mn yield are: high carbon contents in the melt, high process temperatures, high partial CO pressures, high MnO activities [56]. One cost-effective possibility to introduce manganese is the converter process where the blowing can be performed in two steps, and then the final composition will be adjusted in a downstream ladle furnace [56].

Besides a carefully adjusted converter process, the electric arc furnace process is also suited to melt high-Mn steels.

A comprehensive method for making a steel melt containing up to 30 % Mn has been proposed which consists of the following steps: feed a heatable vessel with iron, add basic and, later, Si-containing slag formers, adjust slag viscosity and, finally, alloy with aluminium [57].

Casting. Different problems were reported which occur with high-Mn grades on the conventional slab casting route, e.g. interactions between melt and casting powder, mould sticking/clogging, macrosegregation, oxidation and high bending forces [58]. Nevertheless, the conventional continuous slab casting process seems to be possible [56]. A special selection of casting powders is required. It has to be clarified whether soft reduction can keep center segregation at tolerable levels. Near-net-shape casting methods are to be preferred. It has been proposed [59] that the pre-strip is cast in a twin-roll casting machine and then continuously hot-rolled in preferably one single pass. In [60], a casting roll for a twin-roll strip caster is shown, in which a continuous gas channel is formed, thus discharging the gas and, thereby, preventing the generation of dents on the surface of the strip. Large edge cracks, which were prone to occur in hot-rolled TWIP steels, are avoided by twin-roll strip casting [61]. A method to reduce the hydrogen content already in the liquid phase is presented [62]. The good potential of thin-strip casting for high manganese steels is confirmed elsewhere [63].

As far as the production of high-Mn-steels including triplex steels are concerned, direct strip casting DSC also exhibits advantages compared with conventional slab casting [64; 65]: rapid solidification under a protective gas atmosphere, no friction, the absence of bending, spray water cooling and casting powder, plus a sufficient degree of hot reduction.

The peritectic solidification is particularly detrimental, indeed, it can be caused by higher alloying amounts of aluminium.

Downstream processes. Subsequent production steps, such as, hot rolling, cold rolling and annealing, seem to be less critical if some special features (for example Mn oxide formation) are taken into account. Coating seems to be a matter of concern.

Field of tasks for the continuing development

Steel making route. From the present state-of-the-art it seems to be evident that the efforts are to be continued to find an economic and safe methodology for the production of high-Mn steels, especially for the complex grades with additional elements.

Relation of yield to tensile strength. Characteristic attribute of high-Mn TRIP/TWIP steels is the relatively low yield strength [17]. The possibility of pre-forming to attain higher strength levels on the basis of only a single composition was evaluated. In order to increase the yield stress at a given tensile strength, steels have been manufactured by cold deformation prior to the final processing [66].

High-alloy related coating aspects. In order to guarantee the required corrosion resistance, a high-Mn steel must be corrosion protected by a *coating process*.

Considering hot-dip galvanizing of high-Mn steels, it must be taken into account that an adverse effect on wetting may occur. Appropriate annealing gas atmosphere and surface conditioning may contribute to an improvement of coating properties [67].

Concerning alloy coating, a high-manganese steel is usually hot-dip coated with a layer containing Mn and Fe [68].

Another invention [69] relates to an optimized hot-dip coating in which the steel strip is heat treated in an atmosphere of a defined ratio of nitrogen, water and hydrogen.

Other proposals refer to *pretreatments.* Applying an aluminium coating below the liquid metal coating can improve coating properties [70]. Another benefit is achieved by performing pickling prior to the hot-dip coating, to fully remove the detrimental Mn-oxide [71]. Bright annealing of an X-IP steel affects the Fe/Zn-reaction, and a procedure is presented for better zinc-wetting in a galvannealing process [67].

Delayed fracture in pressed parts. As known from unstable austenitic stainless steel grades, high-Mn steels may also be subject to a damage referred to as *delayed fracture* [17; 34]. This fracture is caused by dissolved atomic hydrogen which is provided either by the steelmaking process or by corrosion. It can easily diffuse and enrich due to the highly stressed microstructure of deformed parts. Cup drawing seems to be particularly critical for hydrogen embrittlement [72]. The risk increases with localized residual stresses due to a restriction of dislocation glide and pile up on only a few lattice planes [73].

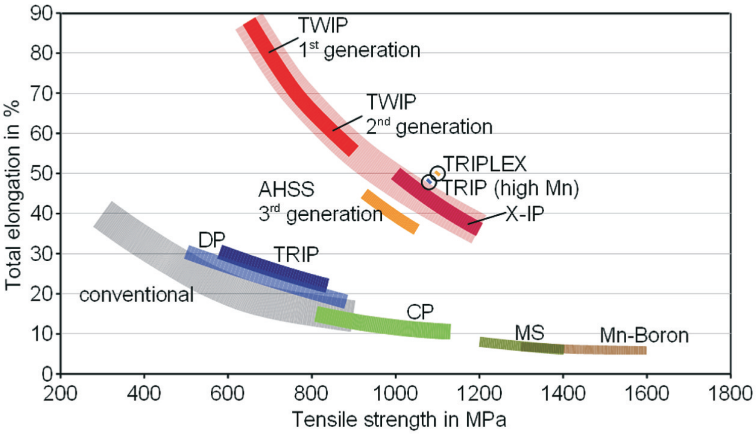


Fig. 9: Comparison of the tensile strength/elongation relation for different steels

A complete suppression of martensitic transformation in TWIP steels by the addition of Al might prevent delayed fracture [74]. Precipitates, if in a suitable size and distribution, can serve as hydrogene traps thereby reducing the risk of delayed fracture quite efficiently [75].

Further effort is to be put on the diminution of the risk of this type of fracture.

Response to marked shear fracture mode. Due to the strong tendency of high-Mn steels to show pronounced shear fracture [34], conventional failure approaches, like the forming limit curve FLC, are not applicable without limitations. A concept of an improved failure analysis is in progress.

Response to dynamic strain aging during forming. During sheet forming processes, DSA can lead to non-homogeneous plastic flow in special high-Mn steel variants [17; 19] and may lead to surface defects on formed parts. DSA can further cause lower elongation values. Since press forming is usually carried out at strain rates in the DSA-free region, it should not be a cause of much concern. In [76], methods to influence dynamic strain aging are reviewed.

High alloy-related joining aspects. High-Mn steels can cause problems in welding [34]. They reveal characteristic thermophysical properties which are taken into account.

The susceptibility of coated high-Mn steels for zinc infiltration into grain boundaries is also quite relevant, especially if additionally alloyed with further elements. Here, special measures are necessary to diminish this problem.

Outlook on market development, competition and application aspects

The potential application of these steels is focused on sheet material revealing proper formability for the fabrication of crash resistant body components possessing high impact resistance under dynamic loading. In addition, these steels are suggested for cryogenic applications [14].

The high-Mn steels must compete with other lower-alloy steels revealing the same objective targets. A comparison with existing grades is shown in **fig. 9**. The low-alloyed advanced high-strength multiphase steels like DP, TRIP and CP are meanwhile well established and widely used. They still reveal further development potential. Low-alloyed Mn-boron steels manufactured by press hardening in a hot forming process are to be considered as a competitive alternative already widely applied to an impressive extent. Another example is the development of medium-alloyed Mn steels, i.e. with less than 10 % Mn [76; 77] which, as AHSS 3rd generation, show better mechanical properties than conventional high-strength steels. Further interesting developments exist which are not included in fig. 9. A promising development relates to the quench and partitioning process for multiphase steels [78]. New carbide-free bainitic steels with residual austenite aiming at improved properties are also under development [79; 80].

Alternative to the austenitic high-Mn steels, special austenitic stainless steels were developed (e.g., 1.4376 X8CrMnNi19-6-3) [81]. Conventional grades like AISI 301, 304 were also evaluated to demonstrate their potential for automotive application [82...84]. A considerable transformation plasticity in these stainless steels is caused by deformation-induced formation of ε and α-martensite. These stainless steels disclose unique corrosion resistance. Stainless steels with combined TRIP and TWIP effects based on Fe, Cr, Mn, and Ni alloy contents were successfully tested as cast material [85]. By superposition of martensite and twin formation, a so far unequalled combination of strength and elongation was achieved for this group of steels.

The development of high-Mn steels faces a number of important technical challenges related to steelmaking, processing and application. The application-oriented development of these steels for mass production and applications on an industrial scale is in progress. Further detailed investigations focus on microstructure-properties relations, the processing and the application are to be continued. Some important aspects are indicated in the above task field which has to be worked off.

To strengthen the theoretical basis for the further operative steel development, the collaborative research center described in [86; 87] elaborates ab initio approaches, based on nature constants together with mesoscopic modelling. New methods for the development with emphasis on high-Mn steels shall be evaluated. An accurate thermodynamic description for the Fe-Mn-C system is in progress as a foundation for further approaches based on modelling.

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