DIRECT STRIP CASTING (DSC) -
AN OPTION FOR THE PRODUCTION OF HSD® STEEL GRADES

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ABSTRACT

With two pilot plants in operation, the **D**irect **S**trip **C**asting (DSC) technology has reached a state from which it can be concluded that a DSC production process is feasible. The core of the process consists of a caster in which liquid steel is fed on an intensively cooled revolving belt. After solidification in a protective atmosphere, the yielded strip of about 10-15 mm in thickness is directly hot rolled without intermediate reheating. Thus, due to the reduced expenditures for hot rolling and reheating, substantial energy savings compared to conventional slab casting can be achieved. Moreover, the production of steels with an increased content of manganese (and carbon), aluminium and/or silicon is enabled by the special features of the DSC process. These new steel grades offer **H**igh-**S**trength and high-**D**uctility (HSD®) properties. The use of these steels in automotive applications would lead to further energy savings induced by significant weight reductions and an enhanced life cycle of the car body. Furthermore, also a higher share of scrap based strip steel production, requiring less than half of the energy needed for the blast furnace route, becomes conceivable for quality steel grades, as a higher content of tramp elements, e.g. copper and tin, is tolerable without quality losses (surface cracks). Finally, the compact design and the high productivity of the DSC process save capital and processing costs. In the paper, process development steps, material properties and energy saving potentials are outlined.

KEYWORDS

Direct Strip Casting, DSC, process development, new steel grades, HSD® steels, energy saving potentials

INTRODUCTION

The development of the DSC process must be seen in the context of other near net shape casting process developments, e.g. thin slab and twin roll strip casting, carried out by European steel making companies in order to produce new steel grades with improved mechanical properties at reduced overall costs and meeting ecological requirements. Complementing conventional hot-rolled strip production short and medium term, near net shape casting is expected to replace conventional slab casting to a significant extent in the long term.

DSC PROCESS: DESCRIPTION - FEATURES - TECHNICAL SOLUTIONS

Fig. 1 illustrates the principle of the DSC process and gives a photo of a pilot caster [1, 2, 3].

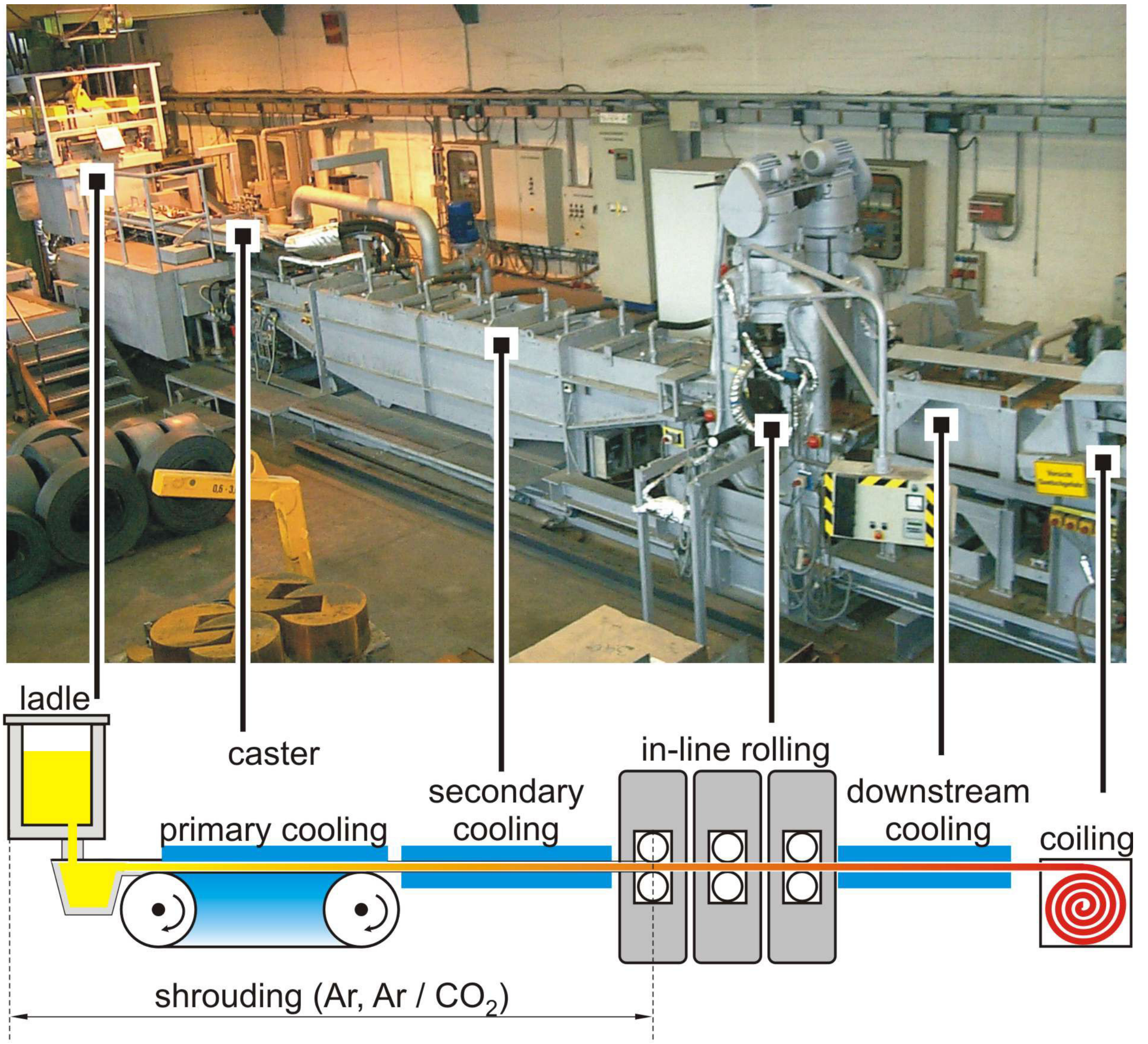

Fig. 1: DSC process scheme and photo of a pilot caster

Process description: The melt is fed on a revolving steel conveyor belt via a dispenser system. The belt, acting like the mould in conventional continuous casting, is intensively water-cooled from below. Solidification (primary cooling) and secondary cooling takes place in a protective atmosphere (shrouding: Ar, Ar / CO_2). Hence, material losses are reduced and adverse effects on product quality due to oxidation are avoided. In the secondary cooling zone, a homogeneous temperature distribution at a level suitable for rolling is adjusted. Afterwards, the yielded strip (cast thickness range: 10 - 15 mm) is conveyed into an in-line rolling mill (3- or 4-step rolling), allowing for a hot reduction of 60 - 70 % necessary for the required mechanical material characteristics, and enabling the coverage of 90 % of the thickness range of a typical hot-rolling mill. The final downstream (tertiary) cooling and the coiler correspond to those used in conventional casting technology.

A pilot plant (**Fig. 1**) was designed and erected for 300 mm strip width. It comprises one-step in-line hot rolling and coiling. Liquid steel is provided by an induction furnace with flexible power lines and cooling water piping, so that it can be handled during casting with a crane like a ladle. Steel flow from the furnace (capacity: 1.3 t) is controlled by a stopper rod. The steel conveyor belt has a thickness of 0.8 mm. The as cast thickness is varied between 10 and 15 mm. A thickness reduction to about 8 mm can be achieved by the one-step hot-rolling mill when starting with 15 mm as cast thickness. Before coiling, the strip passes a three-roll bending system. With typical casting speeds of 8 to 10 m/min, a cast takes between 2 and 3 min and yields a rolled strip of approx. 70 m in length.

Process features: Due to the long primary cooling zone on the conveyor belt (mould), e.g. 10 m in a production facility, and due to the frictionless transport of the strip through the mould, a high throughput of approx. 240 t/h and per metre of cast width at casting speeds of up to 60 m/min becomes conceivable, which is significantly higher than that realised in continuous slab casting.

Moreover, low specific capital and operating costs represent a major benefit of the DSC technology, as **Fig. 2**, based on exemplary calculations [4], reveals. The advantages compared to conventional slab (CSC - **C**onventional **S**lab **C**asting) and thin slab casting (CSP - **C**ompact **S**trip **P**roduction) are attributable to the compact plant design, the high productivity and the lower energy consumption due to the reduction of reheating and rolling expenditures. The latter is outlined in the chapter on energy saving potentials.

Furthermore, the DSC process offers the possibility for the production of new steel grades, especially of grades with high contents of Al, Mn and Si [5]. In contrast to the problems occuring with such grades on the conventional slab casting route, i.e. interactions between melt and casting powder, mould sticking, macrosegregation, oxidation and high bending forces, the DSC process exhibits certain advantages, e.g. the absence of casting powder, mould friction, oxygen, spray water cooling and bending. The avoiding of oxidation results furthermore in enhanced tolerance limits for tramp elements, e.g. copper and tin [6]. These material aspects are further outlined in the chapter on product properties.

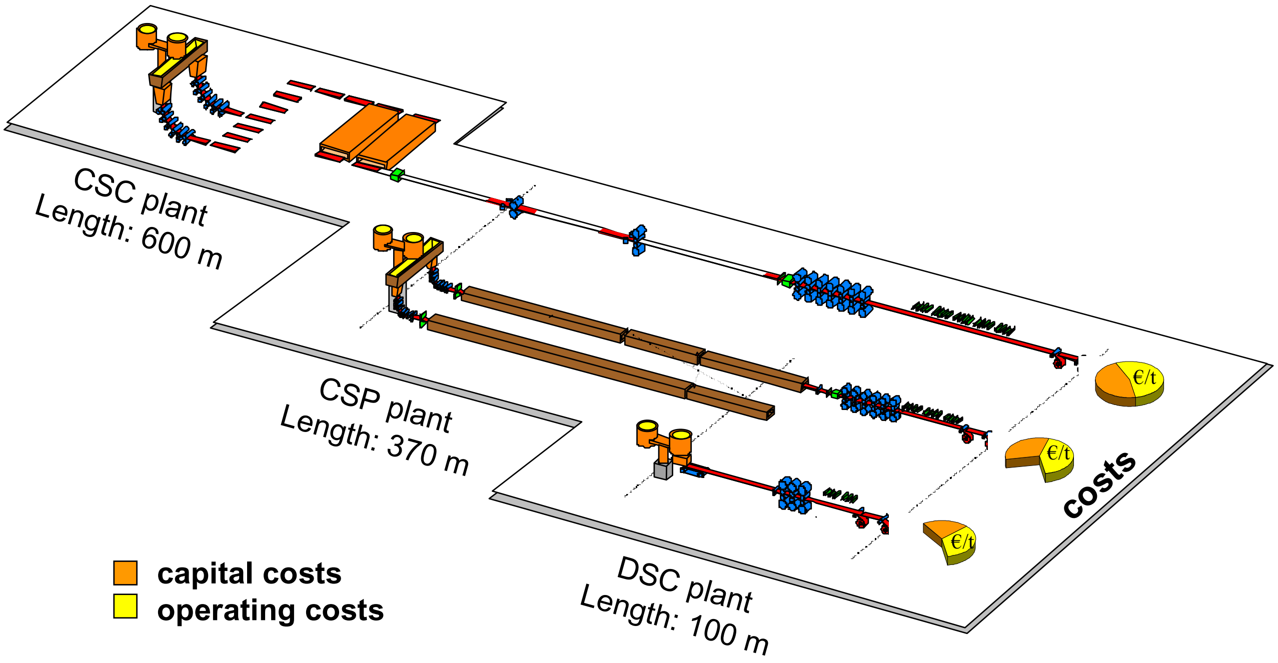

Fig. 2: Layout and costs of different strip production lines (for equal strip output)

Technical solutions:
In the following technical solutions for selected key areas are presented.

Steel feeding: **Fig. 3** shows a sketch of the feeding system. Of special importance is the feeding area where the melt reaches the belt. A uniform distribution of the melt across the belt width has to be ensured. For that purpose and to decelerate the liquid film, argon gas rays are blown against the steel film, acting like a rake.

For an undisturbed solidification, the relative velocities between conveyor belt and steel shall be small. A strong magnetic field, operating like an electromagnetic brake in conventional continuous casting and moving synchronously with the belt is targeted on that [7]. The field is generated by a linear inductor - called "Electromagnetic Flow Synchronisation System" (EFSS; located behind the argon rake and not shown in **Fig. 3**) - which is lowered closely above the melt surface. Moreover, the uniformity of the melt flow profile can be further improved by the inductor application.

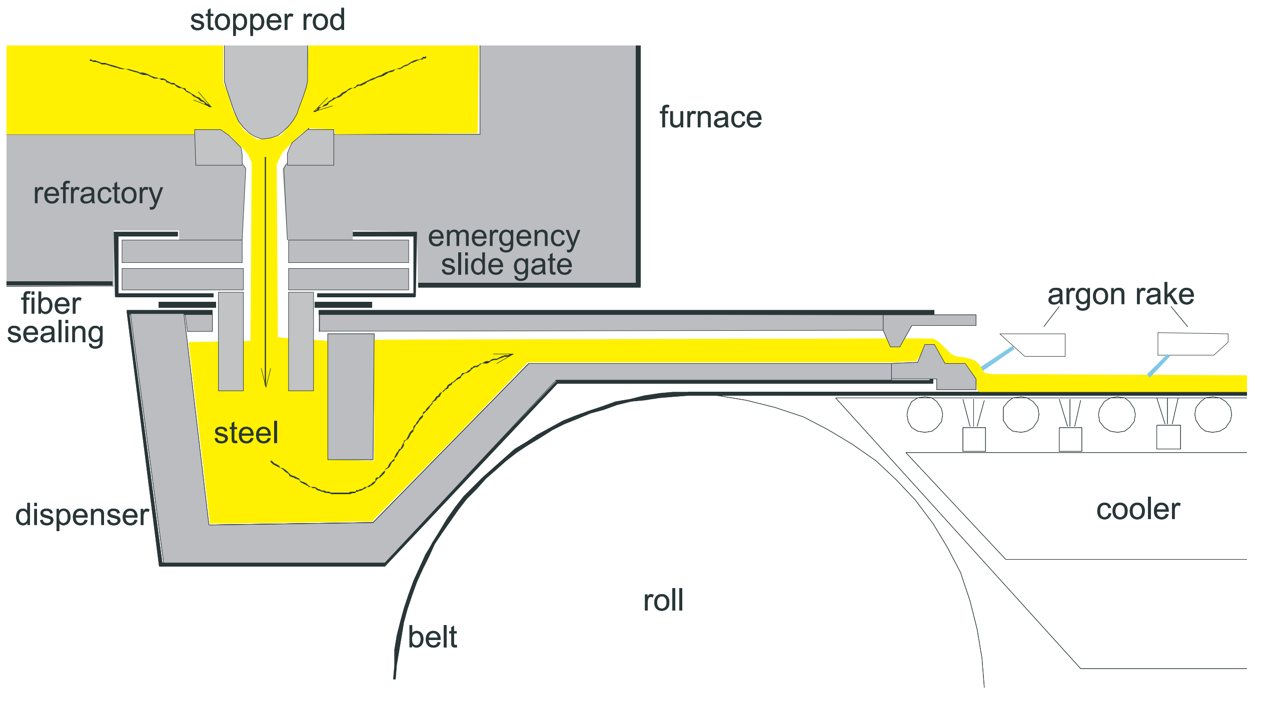

Fig. 3: Steel feeding system

<u>Belt stabilisation</u>: At the beginning of the process development, the melt flow profile was also disturbed by uncontrolled and large-area bulges in the conveyor belt which were induced due to the high thermal impact and the resulting non-uniform expansion of the belt. To solve this problem, the belt is guided over a roller support system with staggered support points on which it is pulled down by a pre-set negative pressure (approx. 0.3 bar) in the cooler. Thus, the inevitable thermal expansion occurs only in the form of a large number of small deflections, limiting the vertical conveyor belt movement to an uncritical amount of below 0.1 mm.

<u>Side containment</u>: Another problem to be solved was the lateral melt containment on the belt. At first, stationary, water-cooled copper ledges were used, resulting in process disturbances (strip breaks) and product defects (edge cracks) due to friction and sticking incidents. Therefore, a moving side dam system, consisting of a revolving chain of copper blocks which are furnished with an internal canal for water cooling, has been developed (**Fig. 4a**). The cooling water supply for the block-chain is realised via flexible tubes and a turnable link (**Fig. 4b**). The block-chain is guided by horizontal tail discs (**Fig. 4a, b**). The front tail discs are driven, and the chain moves synchronised to the belt.

At the top side of the copper blocks, rods are screwed in with bearings for guiding the block-chain in notches along the caster (**Fig. 4c**). The single block-chain elements are connected by segments of high-strength tubes designed for high temperature applications (**Fig. 4d**). At the end of the tube-segments junctions are placed with right-hand and left-hand screw threads, respectively. In the blocks there are corresponding internal screw threads. So, by screwing in the connecting tube-segments the blocks are brought into contact, still allowing bending to one side.

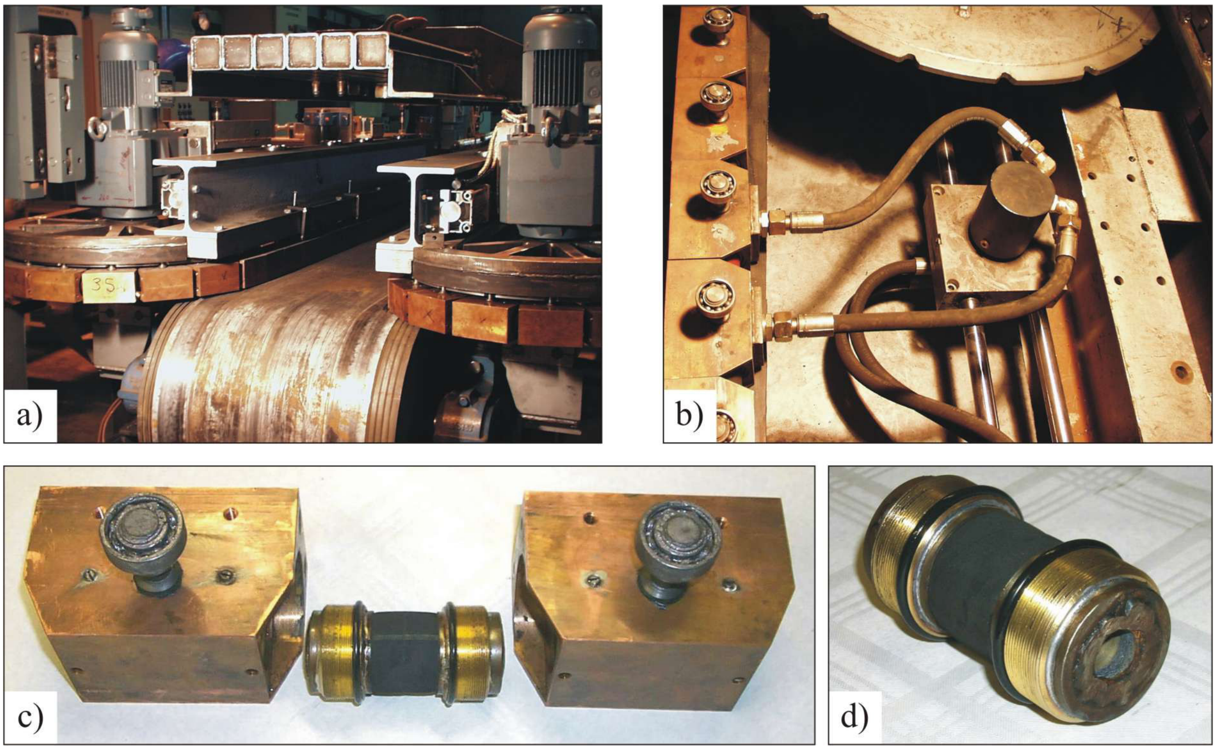

Fig. 4: Design of the moving side dam system

<u>Top side cooling</u>: To avoid the formation of slag on the melt due to the presence of oxygen and, hence, a product surface of unacceptable quality, solidification takes place under a shrouding atmosphere of argon but which is blended with a few percent of CO_2. Under a pure argon atmosphere, heat removal and solidification is predominantly single-sided towards the intensively cooled bottom strip side, as the melt surface preserves its metal shine, i.e. a low emissivity, and dissipates only a small amount of heat. That leads to final solidification close to the top surface and to a porous upper strip surface.

The presence of CO_2 initiates more homogeneous cooling of the strip from above and below. This effect occurs due to supercooling as carbon content in a thin melt layer is reduced by the CO_2, causing the solidification of a thin film at the upper strip surface. In turn, this film provides both the nuclei for further solidification and an increased surface emissivity. Hence, solidification from the surface is accelerated, and the final solidification zone is shifted towards the strip centre, where potentially occurring microporosity is closed during hot rolling without problems.

<u>Synchronisation of rolling and coiling</u>: As casting and rolling / coiling steps are coupled in the DSC process, a suitable synchronisation is required. Concerning the thickness of the cast strip, it is determined by the melt mass flow controlled by the furnace stopper rod in connection with the conveyor belt speed. At start of casting, a cold strip that pulls the cast strip over the roller table into the open rolling gap of the in-line rolling stand runs at the same speed as the conveyor belt. A thermal sensor detects the passing of the head end of the cast strip through the rolling gap and initiates the adjustment of the gap to its set value. In front of and behind the rolling stand, speedometers are located to measure the strip speed. Taking into account the shrinkage of the strip,

the rolling speed is controlled based on a roll gap model so that it corresponds to the conveyor belt speed.

PRODUCT PROPERTIES

The product properties achieved for conventional steels have already been described [1, 3, 6].

Influence of tramp elements: Due to the shrouding, higher contents of tramp elements in the steel, e.g. copper and tin, can be tolerated as the susceptibility to crack formation caused by the surface enrichment induced by selective oxidation virtually disappears (**Fig. 5**).

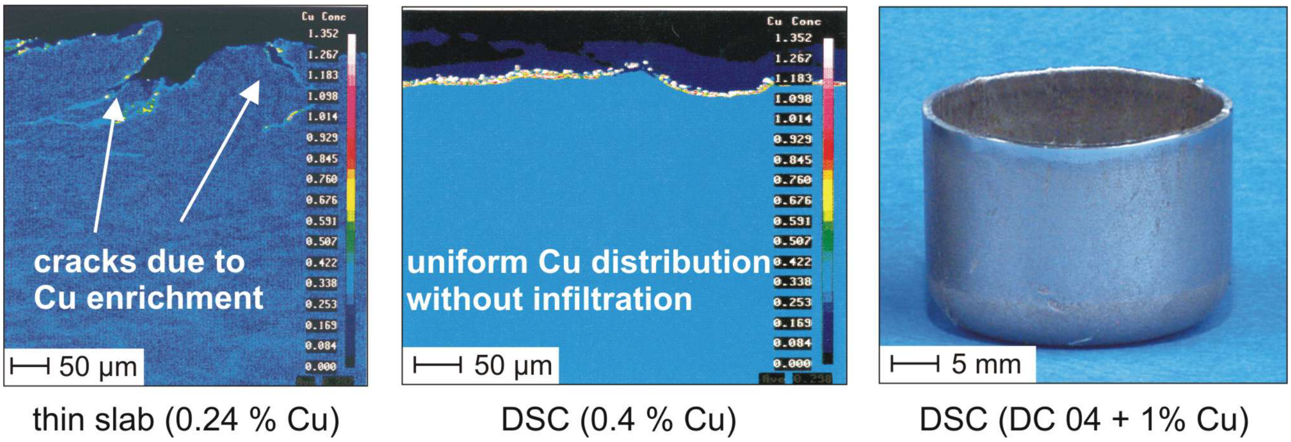

Fig. 5: Effects of alloying / tramp elements on surface quality

Hence, recycling capability of steel scrap is extended, and potentials for copper to be used as an efficient corrosion-inhibiting alloying element arise. For instance, alloying a medium carbon steel with 1 % Cu was found to reduce the corrosion rate in a 3.5 % NaCl-solution to less than 10 %.

High Mn-containing TRIP / TWIP HSD® steels: The characteristics of the DSC process, i.e. rapid solidification under a protective gas atmosphere, no friction, the absence of bending, spray water cooling and casting powder, and a sufficient degree of hot reduction, offer, as mentioned, prospects for the production of new steel grades with higher amounts of alloying elements, e.g. Mn (≈ 10-27 %), Si (< 3 %), Al (< 6 %) and C (< 2 %). These grades cannot be cast on the conventional route and, above all, outperform steels known today with regard to strength and ductility. These new steel grades provide **H**igh-**S**trength and high-**D**uctility properties at the same time and are therefore called HSD® steels.

In numerous test trials at the pilot plant, the castability of such FeCMnAlSi alloys by the DSC process was proven. The shape and the edge quality of the freely coiled strip was good, as was the surface quality, as **Fig. 6** reveals. An improvement of the surface quality was achieved by belt structuring and by the use of belt coatings (e.g. nickel).

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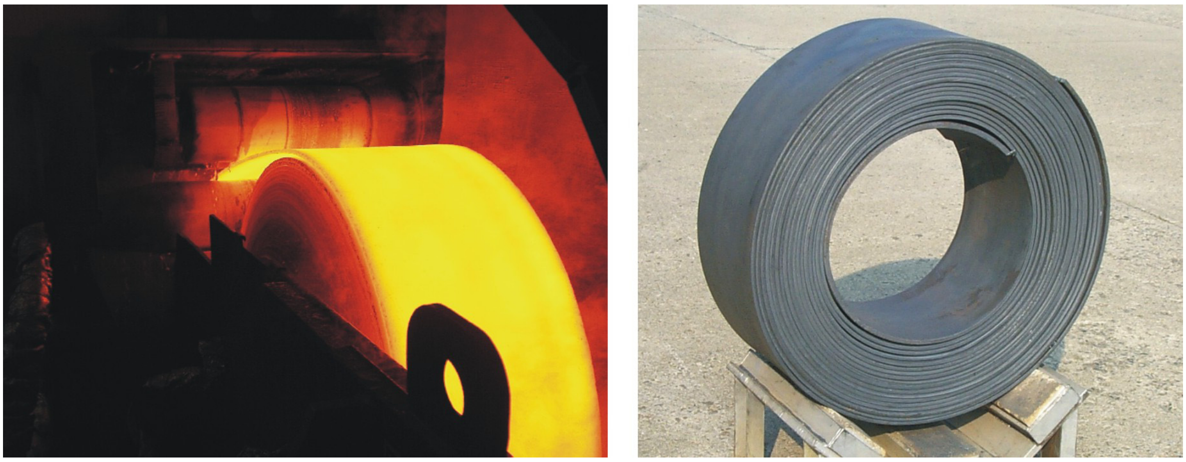

Fig. 6: Strip cast on the pilot plant

The enhancement of strength and ductility values, compared to conventional steels, is achieved by using the TRIP- and TWIP-effect which depend on chemical composition and process control. As illustrated in **Fig. 7**, the FeCMnAlSi alloys produced both in a laboratory process (MPIE - Max-Planck-Institut für Eisenforschung) and on the DSC pilot caster show an extraordinary strength-ductility ratio [8].

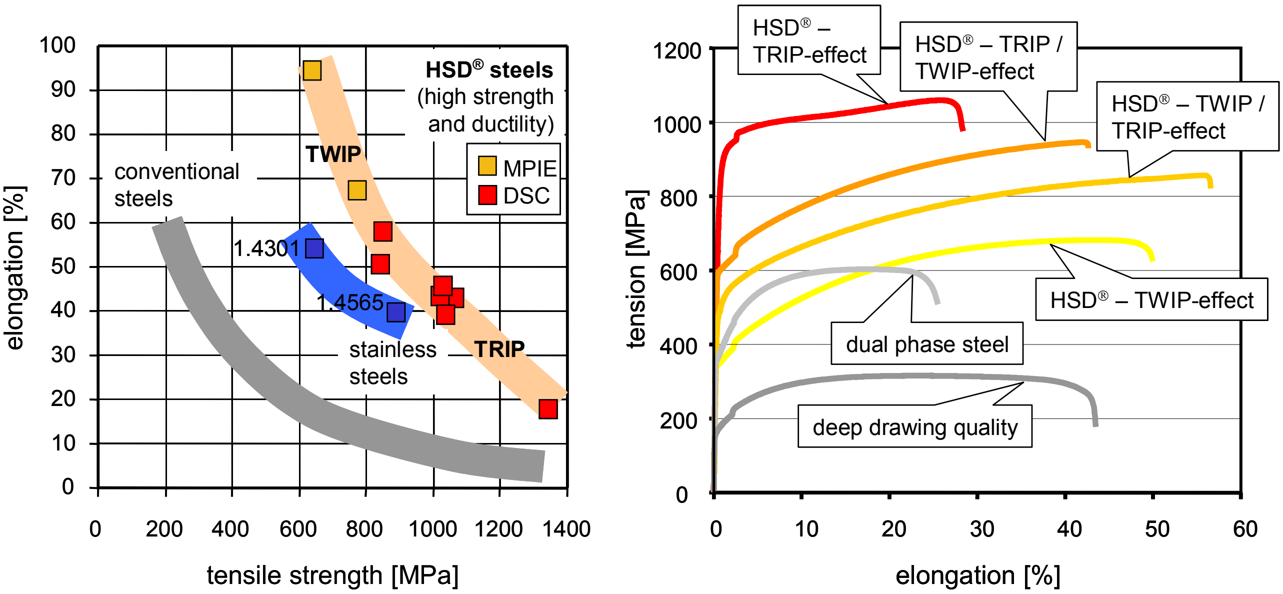

Fig. 7: Ductility versus strength for conventional and FeCMnAlSi HSD® steels

By **Fig. 8**, it becomes obvious that an extremely wide range of mechanical properties can be achieved by proper heat treatment of FeCMnAlSi steels. Starting with cold rolled strip, annealing at low temperatures leads to increased strength data due to a type of bake hardening effect, whereas high temperature annealing yields materials of high ductility with a still high strength level. So, in addition to the extraordinary properties, these types of steels are extremely flexible regarding the adjustment of those properties which are most suitable for subsequent post processing. In principle, even the local properties of components can be optimised, e.g. to achieve a defined and improved crash behaviour.

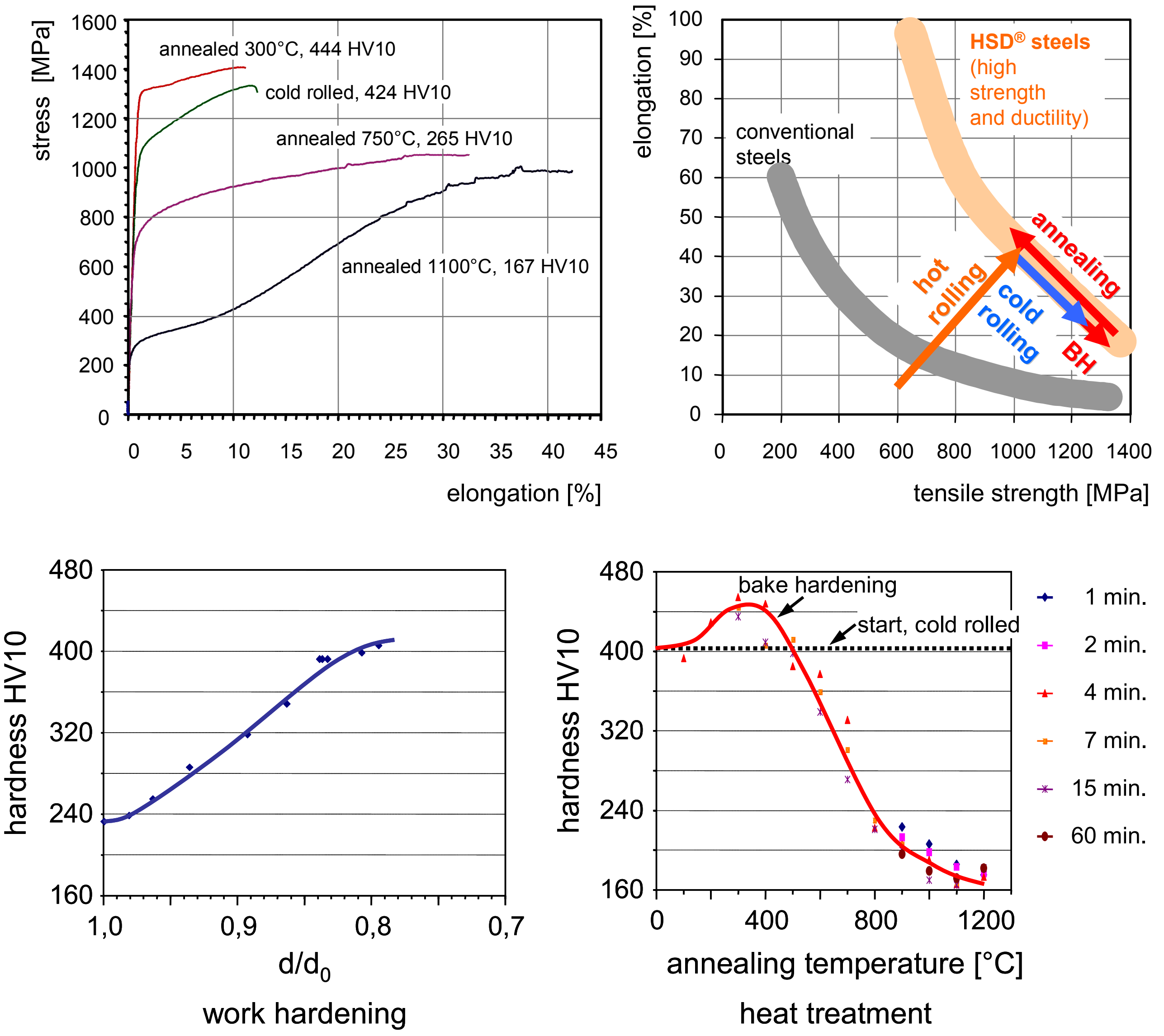

Fig. 8: Property adjustment by heat treatment (MnAlSi 15 2.5 2.5) at different temperatures and for different annealing times

The importance of sufficient hot rolling - possible with the DSC process - for grain structure development and, hence, for the hot strip's mechanical properties is outlined by **Fig. 9**. Good hot strip properties are a prerequisite to obtain a high-quality cold strip, especially for those TRIP steels where the strength results from deformation and is therefore related to ductility.

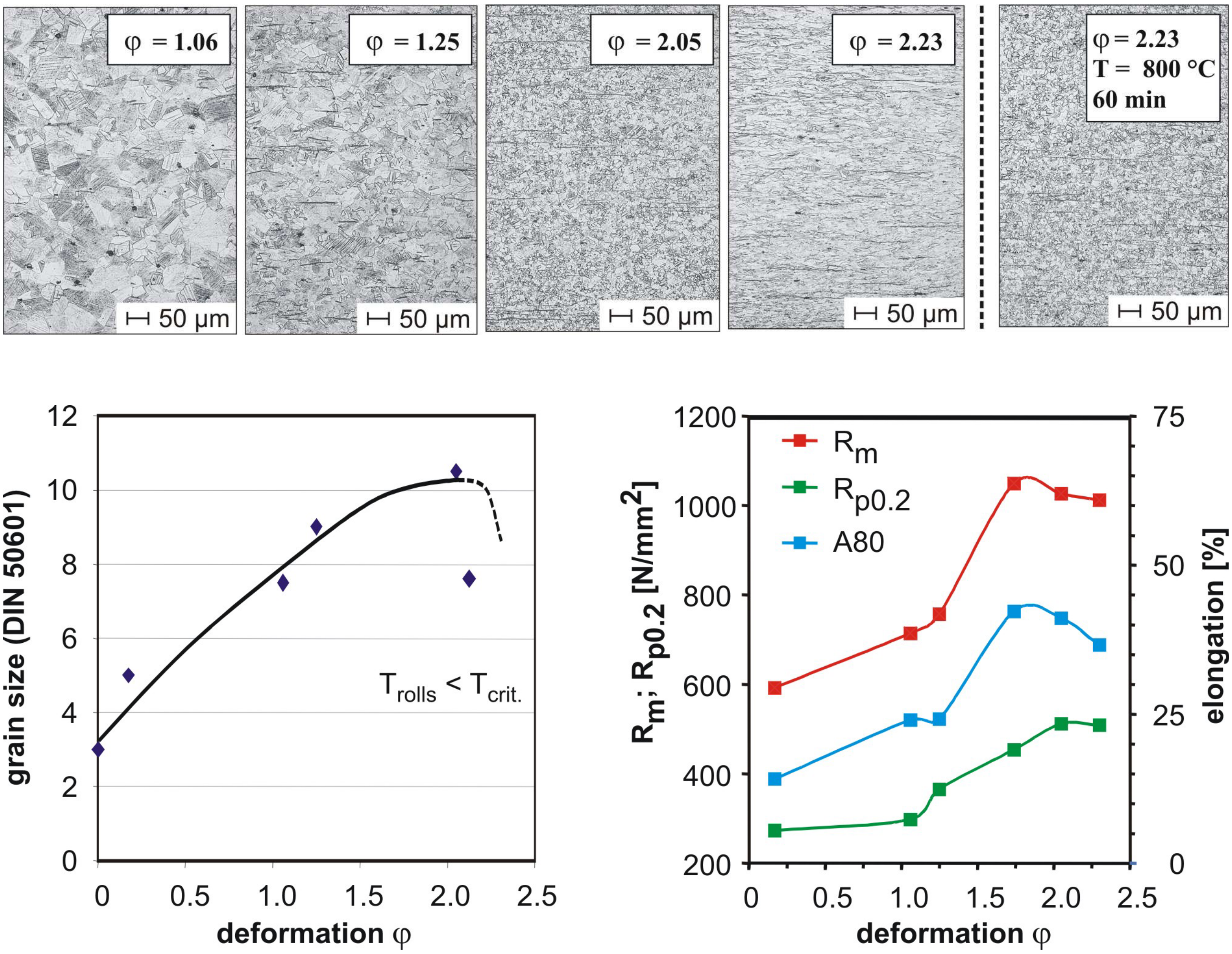

Fig. 9: Importance of hot rolling (MnAlSi 15 2.5 2.5); effect on structure and mechanical data

ENERGY SAVING POTENTIALS

In the context of economical and ecological boundary conditions, the reduction of primary energy consumption and, therefore, the reduction of CO_2 emissions is gaining more and more significance. Thus, to exemplify the dimensions of possible impacts of a long-run general launch of the DSC technology on the primary energy demand, three fields have been investigated:

- casting / rolling process
- extended scrap use
- application of new light-weight steel alloys (car bodies)

Casting / rolling process: The production step reduction by the direct coupling of casting and rolling in the DSC process (see **Fig. 2**) and the near net shape thickness leads to a decrease of reheating and rolling expenditures. **Fig. 10** contains a comparison of the specific primary energy demand for CSC (**C**onventional **S**lab **C**asting), CSP (**C**ompact **S**trip **P**roduction) and DSC processes [4, 9, 10].

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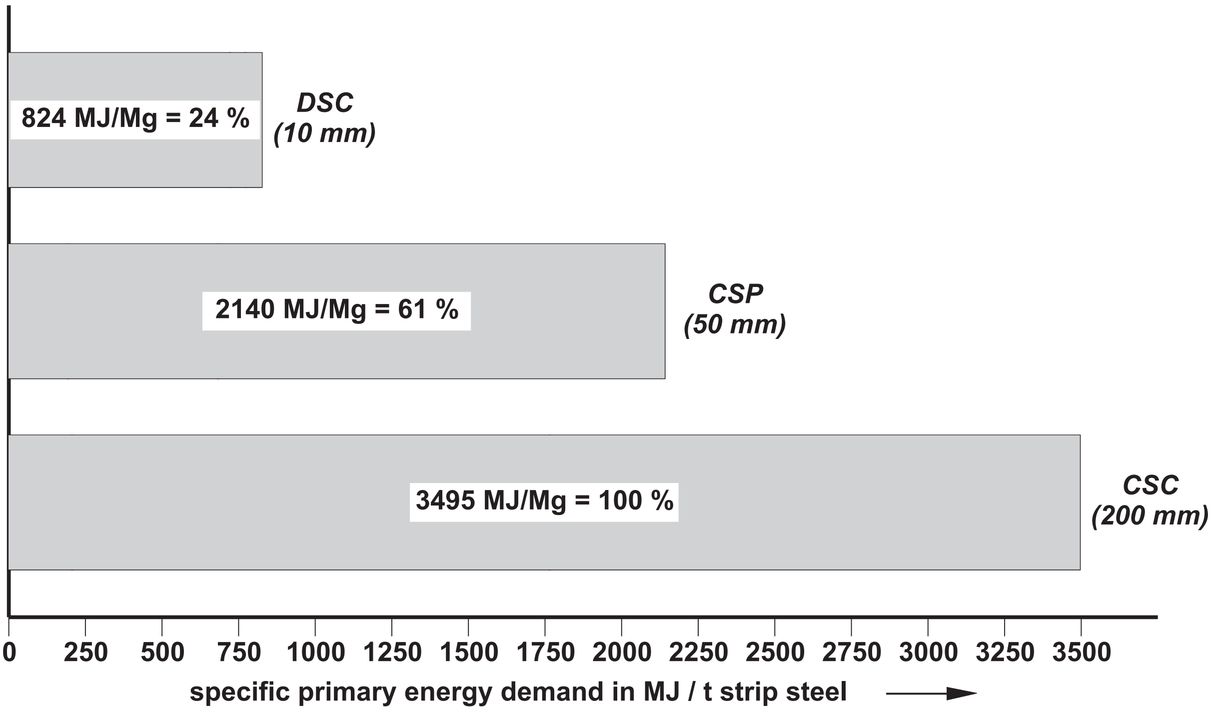

Fig. 10: Primary energy expenditures for CSC, CSP and DSC (casting and rolling)

It becomes obvious that the primary energy demand for the DSC casting and rolling procedures only amounts to about a quarter of that necessary for the CSC process. Compared to the expenditures of CSP, approx. 40 % are required.

Thus, the primary energy saving potential of the DSC process, compared to CSC, amounts to approx. 2.67 GJ per t strip steel. Taking into account an annual German strip steel production of 25 mill. t [11], and assuming 50 % being DSC cast, an energy saving potential of about 33 PJ/a would arise.

Extended scrap use: As already outlined in the previous chapter, the higher tolerable content of tramp elements in melts to be direct strip cast opens up enlarged possibilities for the use of scrap in the production of quality strip steel. The replacement of oxygen steel produced on the blast furnace-converter route by electric steel from the EAF path would also be accompanied by primary energy savings, as the production of 1 t oxygen steel requires 19.2 GJ of primary energy, whereas the same amount of electric steel is charged with 7.5 GJ [12, 13, 14], i.e. a saving of 11.7 GJ per t strip steel.

Application of new light-weight steel alloys: As explained above, TRIP- and TWIP-effect revealing FeCMnAlSi steels cannot be cast by conventional processes like CSC and CSP, but on DSC plants. The possible adjustment of a wide variety of mechanical properties, together with the light-weight characteristics, suggest an application of these materials in car body design.

Due to the reduced material density and the improved mechanical properties, a weight reduction of 20 %, compared to conventional steels, by the use of FeCMnAlSi alloys can be estimated [4]. In the case of an average automotive body of 300 kg, this results in a weight reduction of 60 kg. In literature, widely scattering values for the specific fuel consumption reduction between 0.1 and 0.7 litres per 100 km run and 100 kg weight reduction can be found [15, 16]. Considering for instance a mean value of 0.3 l/(100km·100kg), that leads to fuel saving potentials up to approx. 35 PJ/a, i.e. more than 2 % of the actual primary energy consumption for auto fuels, as **Fig. 11** illustrates for the case of a 20 % weight reduction for all automotive bodies.

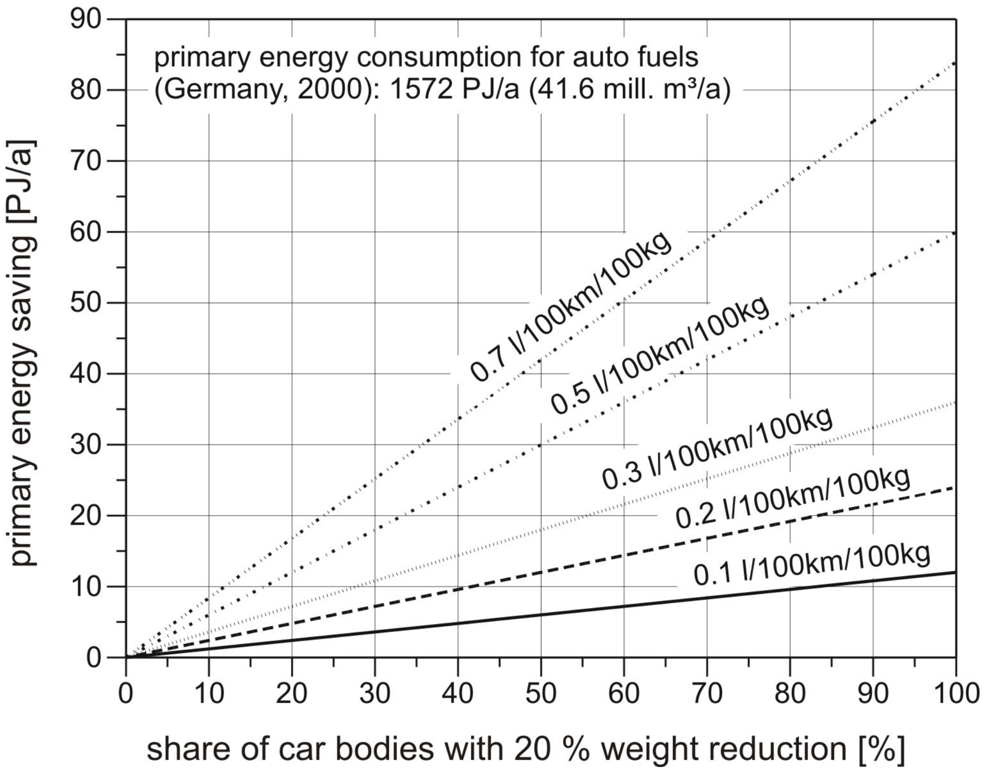

Fig. 11: Fuel saving potentials by FeCMnAlSi application in car body manufacturing [15]

SUMMARY AND CONCLUSIONS

After research and development activities in laboratories and on pilot casters, the DSC process has reached a state from which it can be concluded that a production process is feasible. Such a process will be characterised both by a high degree of productivity and comparatively low capital and operating costs. It will enable the production of new light-weight materials showing outstanding **h**igh **s**trength-**d**uctility behaviour (HSD® steels) and a low specific weight, as the process - in contrast to the conventional slab and thin slab casting routes - allows for the use of enhanced amounts of alloying elements like manganese, aluminium and silicon.

Moreover, the energy efficiency of the process is remarkable due to reduced reheating expenditures and optimised rolling efforts. Besides these direct effects, indirect energy saving potentials occur e.g. due to the possible extension of scrap recycling ratio for strip production, as tramp elements can be tolerated - or are even welcome, e.g. as corrosion inhibitors -, or as a consequence of the application of the new light-weight steel alloys in the transportation sector (e.g. automotive bodies).

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HOME

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