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Versatile Dual Phase Steels: Balancing Hole Expansion and Elongation

M. Bechtold[1)], N. Kwiaton[1)], C. Lesch[1)], F. B. Klose[1)], A. Holdinghausen[2)], S. Schulz[2)]

[1)] Salzgitter Mannesmann Forschung GmbH, Eisenhüttenstr. 99, 38239 Salzgitter
[2)] Salzgitter Flachstahl GmbH, Eisenhüttenstr. 99, 38239 Salzgitter

Summary

Dual phase (DP) steels have been established for several decades and are widely used for automotive applications. They have numerous advantages compared to other advanced high strength steel sheets (AHSS): large spectrum of strength levels due to adjustable phase fractions, size and distribution of ferrite and martensite in combination with a proper formability, relatively lean composition ensuring good workability and weldability, broad availability in a wide range of gauges and coating types. As there is an ever increasing need for weight savings at improved performance, DP steels have to cope with high demands on edge crack insensitivity, necking resistance and crash worthiness. This work shows that DP steels can be optimized depending on customers demand either in terms of hole expansion or elongation. This can be provided by adjusting the microstructural features during processing without significant increase in alloying content.

Keywords

Dual-phase steels, hole expansion, formability, elongation, microalloying, microstructure, precipitation

Introduction

DP steels have been studied for several decades and there is an enormous load of publications referring to metallurgy, microstructure evolution and properties [1-3]. Along with the extensive use in autobody components, the customers' demands for improved properties are ever increasing. At the same time, methods for microstructure characterization and simulation tools are advancing quickly [4, 5], helping to understand the metallurgical mechanisms. Hence, there are increasing possibilities for investigating DP steels. In this work, we focus on hole expansion and elongation, which are both crucial properties for automobile manufacturers who intend to increase the complexity of a formed part or to save weight by reducing the sheet thickness.
Table 1 lists the main metallurgical and microstructural factors that influence hole expansion capacity and formability in terms of uniform and total elongation. It is obvious that some features (e.g. reduced segregations) are beneficial for both properties, while others (e.g. bainite) enhance only one of them. In materials development, these microstructural features need to be well-balanced considering efficiency, process stability, cost efficiency and performance.
In this paper, several examples are introduced which show the beneficial effects of some of these metallurgical features. The study comprises both laboratory and industrial cold rolled and annealed materials at strength levels between 600 and

1000 MPa. A detailed metallographic characterization is performed applying light optical microscopy (LOM), scanning electron microscopy (SEM), electron backscatter diffraction (EBSD), X-ray diffraction (XRD and transmission electron microscopy (TEM). The mechanical properties are characterized by tensile tests, bending tests (according to VDA 238-100) and hole expansion tests (according to ISO 16630), as well as by the forming limit curve (FLC).

Table 1: Metallurgical and microstructural factors that influence hole expansion capacity and formability (elongation).

Improving…	
Hole expansion ratio	**Formability (elongation)**
Reduce hardness difference by - alloying concept - grain refinement - precipitation / solid solution strengthening - tempering of martensite	Reduce martensite fraction, compensate loss in strength by - grain refinement - precipitation / solid solution strengthening
Reduce precipitation size	
Reduce inclusions	
Reduce segregations / banded microstructure	
Increase bainite fraction	Reduce bainite fraction
Reduce metastable austenite	Introduce metastable austenite

Results

Example 1: DP600

This example shows how the careful adjustment of the alloying concept can substantially influence the hole expansion capacity. In Fig 1, the chemical composition of two steels is given along with the mechanical properties after a conventional hot dip galvanizing annealing treatment in a continuous line. There are several changes in the alloying elements that lead to a significant increase of the hole expansion ratio at constant strength levels in steel 2: First, carbon is reduced from 0.13 mass% to 0.09 mass% leading to a decrease in martensite hardness. On the other hand, silicon and niobium enhance ferrite hardness by solid solution strengthening (Si), precipitation strengthening and grain refinement (Nb), respectively. Hence, the hardness difference between ferrite and martensite is decreased. Furthermore, phosphor is reduced to a technical minimum in order to diminish segregations. Chromium is replaced by manganese for cost efficiency. These measures allow the hole expansion ratio to be significantly increased, wherein the reduction in the carbon content has the greatest effect. As some of the features also improve formability (see Table 1), uniform and total elongation are also slightly increased.

Composition, mass.%		
	1	**2**
C	0.13	0.09
Si	0.1	0.25
Mn	1.3	1.8
P	0.03	-
Cr	0.6	0.3
Nb	-	0.01

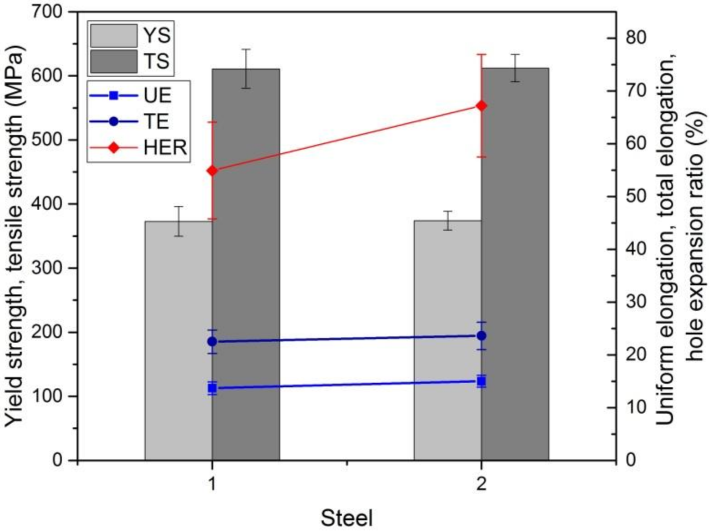

Fig. 1: Example for the influence of the alloying concept on mechanical properties (DP600). n is sample size.
Steel 1: n (tensile test) = 325, n (hole expansion test) = 319,
Steel 2: n (tensile test) = 600, n (hole expansion test) = 352.

Example 2: DP800 (SiAl)

It is known for quite a long time that sufficient amounts of Si and Al lead to an increase of the retained austenite content when a specific heat treatment is applied. This heat treatment must comprise an austenitization followed by a holding period in the bainitic transformation regime [6]. As Si and Al do not form carbides, a carbide-free bainite is formed, the excessive carbon diffuses into austenite and stabilizes it. The retained austenite is metastable and transforms into martensite during forming or in case of crash. This generates fresh dislocations that contribute to an increase in strength and ductility (Transformation Induced Plasticity, TRIP effect). These TRIP steels generally contain higher amounts of carbon than DP steels (~0.2% vs. 0.10-0.15%) and the sum of Si+Al is normally > 1.5%. This leads to specific challenges during steel processing, e.g. interaction with the casting powder, poor wetability and zinc adhesion during hot dip galvanizing [7]. More importantly, the high alloy contents may cause significant problems during manufacture and application processes. Welding is complicated due to the high carbon equivalent and the appearance of liquid metal embrittlement (LME). Furthermore, TRIP steels are known to be susceptible to hydrogen embrittlement [8, 9] and exhibit similar hole expansion capacities compared to DP steels.
A recent study on laboratory materials showed that significant amounts of retained austenite can also be achieved with lower C and sum of Si+Al. Fig 2 shows the results of tensile tests and retained austenite measurement via a magnetic testing device on laboratory melts with constant C content (~0.15%) but varying the sum of Si+Al (0.6-1.1%). The melts were hot and cold rolled and annealed according to a conventional hot dip galvanizing process. The retained austenite content increases significantly with the sum of Si+Al content, as well as the total elongation. At the same time tensile strength is slightly increased.

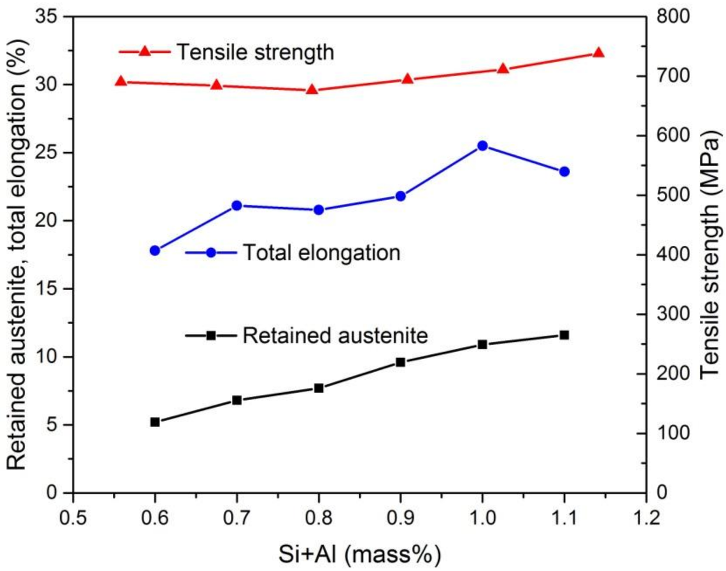

Fig. 2: Influence of the amount of silicon and aluminum on retained austenite, total elongation and tensile strength (hot and cold rolled laboratory material annealed according to a conventional hot dip galvanizing heat treatment). Other elements (in mass%): C ~ 0,15, Mn 1,8 - 2,0, Cr < 0,2, Nb ~ 0,02

Hence, the addition of even relatively low amounts of Si and Al at lean carbon levels can lead to significant improvements of the mechanical properties. Data on hole expansion capacity and other application properties need to be collected to fully establish a comparison with conventional DP and TRIP steels.

Example 3: DP800 (CrNb, VNb)

Apart from changing the chemical composition of the steel it is possible to optimize the properties by adjusting the process parameter. In this example, the properties of a steel possessing the following chemical composition (CrNb-DP-steel in mass%: 0.15 C, 2.0 Mn, 0.4 Cr and 0.02 Nb) were optimized by subjecting the material to different annealing conditions. In this case different cooling conditions were realized to effect the mechanical properties (Fig 3) and microstructures (Fig. 4).

The optimization could be realized in view of different ways, i.e. improved elongation, xpand® with improved hole expansion ratio (HER) or balancing both. In the case of an optimization in terms of improved elongation the hole expansion ratio is clearly lower. On the other hand, after improvement in terms of hole expansion ratio (HER) the uniform and total elongation is reduced. The balance state offers a compromise between elongation and hole expansion, which makes this material attractive for general use. The change in mechanical properties is also reflected in the microstructure. The material with high elongation shows a mixture of ferrite, martensite and bainite, whereas the materials with high hole expansion and in the balanced state show in addition portions of tempered martensite. However, it can be ascertained that an increasing amount of bainite leads to an improved hole expansion ratio.

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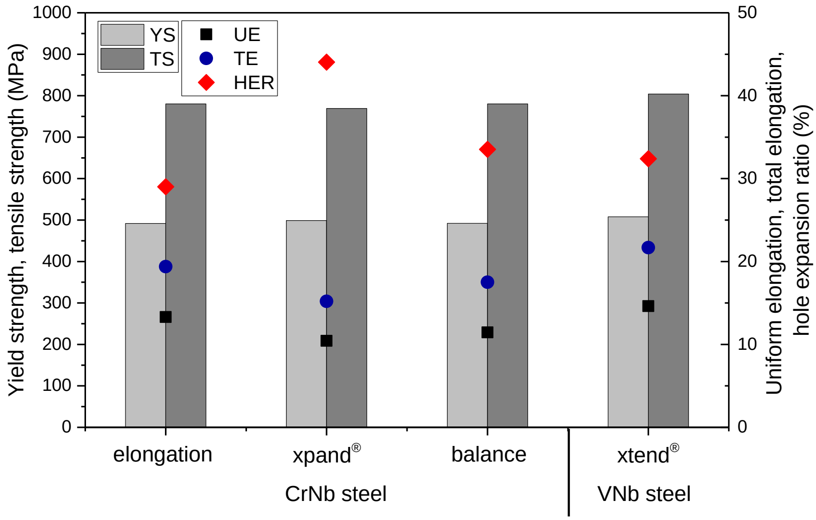
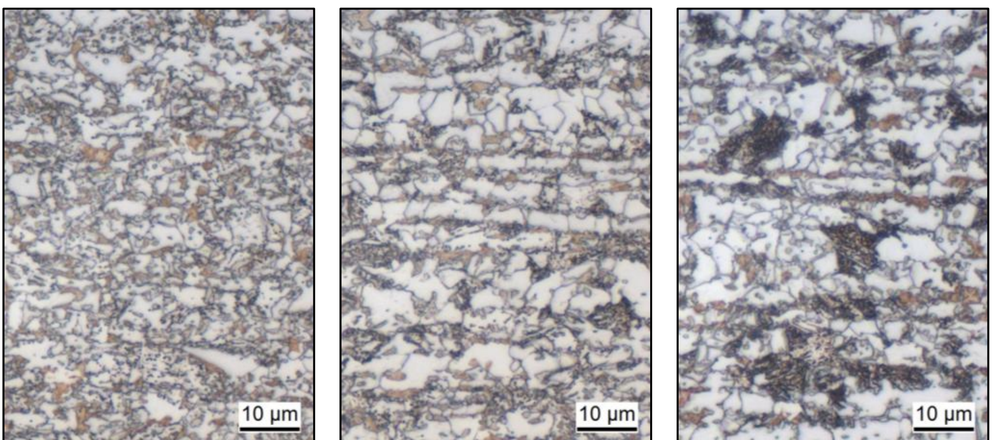


Fig. 3: Mechanical properties of CrNb steel optimized in terms of elongation, hole expansion (xpand®) and balanced properties. In comparison, the properties of VNb steel (xtend®) are exhibited, with its pronounced elongation capacity.



Elongation xpand® Balance

Fig. 4: Comparison of the microstructures of CrNb-DP-steel optimized in terms of elongation, hole expansion (xpand®) and balanced properties.

However, the customers demand more and more steel grades with excellent formability capacities, which is expressed by both, improved elongation properties AND good hole expansion, simultaneously. To achieve this goal, the steel was alloyed with vanadium and niobium (VNb-DP-steel in mass% 0.15 C, 1.8 Mn, 0.15 V+Nb). The mechanical properties are shown in Fig. 3 (right column) This steel even achieves a higher uniform and total elongation and shows also a good hole expansion, which in turn results in an improved stretch-flangeability.
When comparing the microstructures of CrNb-steel (Fig. 4) and VNb-steel (Fig. 5)), a clear grain refinement is achieved for the VNb-steel, which is considered for all microstructural components, the ferrite phase as well as the martensite. The fine

precipitates are more difficult to detect, therefore TEM investigations have been carry out. Fig 6 shows the result of TEM on a sample after galvanizing. Fine niobium-vanadium carbides in the range of 10-50 nm and niobium carbides in the range of 2-50 nm were found. Due to the substantial grain refinement and the population of very fine precipitates excellent mechanical properties are obtained. The elongation is further improved by a reduction of the bainite fraction, whilst the hole expansion capacity in turn is slightly reduced, but still on a good level.

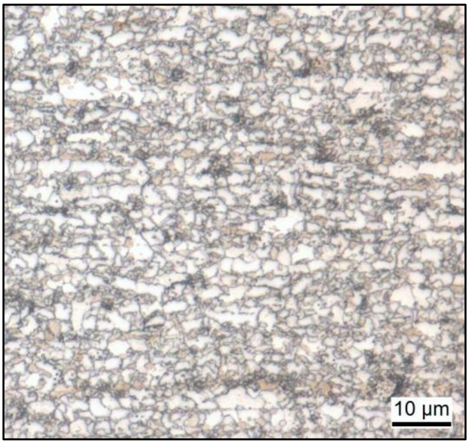


Fig. 5: Microstructure of NbV-DP-steel

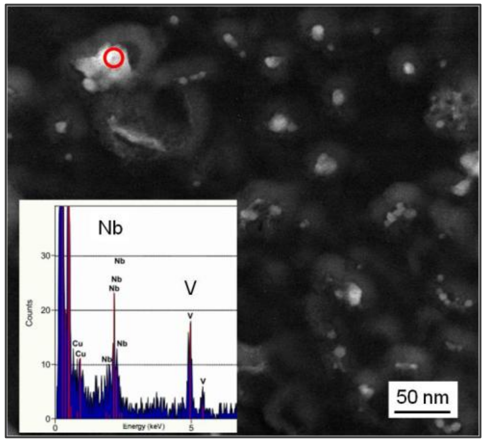


Fig. 6 Microstructures: analysis with TEM shows fine precipitates of (Nb,V)C

Example 4: DP1000

As listed in Table 1, tempering of martensite is one effective way to improve hole expansion ratio, which is due to the reduction of the hardness difference between ferrite and martensite in the microstructure. For this study, industrial cold rolled material (~ 1 mm thickness) was subjected to intercritical annealing followed by rapid cooling to produce a DP1000 (CR700Y980T-DP). In case 1, the direct quenched (DQ) material was tested without further treatment. In case 2, the material was subjected to an annealing cycle including tempering treatment (TM). Both materials contain (in mass%) 0.15 C, 0.2 Si, 2.0 Mn, 0.4 Cr and 0.02 Nb.
In Fig 7, the microstructural components are compared based on light optical microscopy. While both materials contain around 40% ferrite and 60% martensite, two-thirds of the martensite in the TM material are tempered which is easily resolved by the black color of the martensite in comparison to the brown color of the untempered martensite.
The influence of the tempered martensite fraction on the properties of the tensile test is quite low (Fig 8a). The tensile strength is slightly reduced due to tempering. However, this can also be an effect of a slightly changed composition or varying phase fractions. A slight increase of the hole expansion ratio was detected, but more significantly, the bending angle increases both parallel and transversal to the rolling direction upon tempering of martensite.

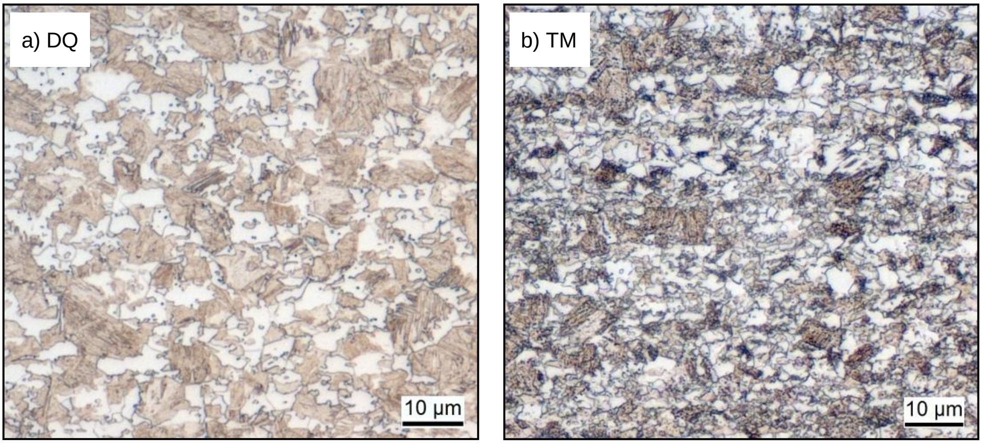


Fig. 7: Comparison of the microstructures in case 1 (direct quenched, DQ) and case 2 (tempered material, TM). The martensite fraction is around 60% in both cases, while two-third of the martensite in the TM are tempered.

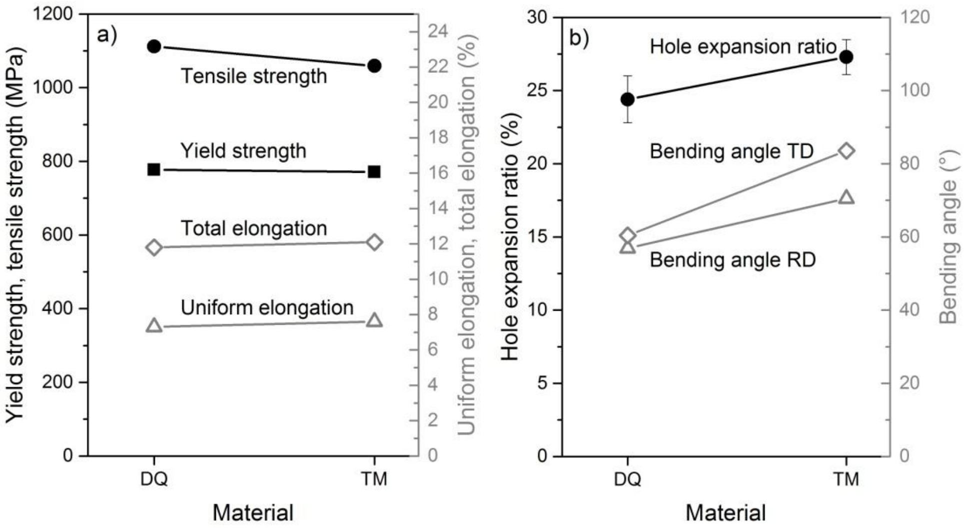


Fig. 8: Influence of tempered martensite on the mechanical properties in case of DP1000. The tempered material (TM) shows nearly the same properties in the tensile test, slightly higher hole expansion ratio, but significantly increased bending angle.

Comparison of the forming limit curves (FLC's) shows only slight differences. While the DQ material shows better formability in the inflexion point near the plane strain deformation, the materials are very similar in uniaxial and equi-biaxial forming mode.

Conclusions

Dual phase steels are versatile and can be optimized for a variety of applications. Some possibilities to improve the properties were presented here with different

examples. Which method of improvement is used depends on i) the requirements of the customers (high elongation, high hole expansion, etc.) ii) the technical restrictions, in terms of both overall production steps and individual plant configuration, and, of course iii) the final costs of the chosen production route.
This contribution shows that by changing process parameters the microstructural features can be decisively adjusted, and thus the mechanical properties improved:

- influence of bainite/tempered martensite fractions on elongation and hole expansion. (example 3), and
- the improvement of hole expansion by tempered martensite (example 4)

On the other hand different analytical approaches can support improving the mechanical properties:

- reducing the hardness difference in microstructure by using an alloying concept with lower carbon content to improve hole expansion ratio (example 1),
- introducing small amounts of metastable austenite to improve elongation by alloying Si and Al (example 2) and
- usaging grain refinement and precipitation strengthening by microalloying with V and Nb (example 3).

Nowadays a dual-phase steel is hardly comparable with a dual-phase steel from the beginning of the 1990s. The properties were continuously developed for costumer's requirements within the global standard and their microstructure has evolved from pure ferrite/martensite to a more and more complex structure with specific microstructural features such as bainite, retained austenite and a mixture of fine precipitates.

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