Investigation on local mechanical properties in multiphase steels for designing local properties of constructional elements

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ABSTRACT

The investigation deals processes leading to local strengthening in multiphase steels, being characterized by a good formability, continuous yielding, high strength and a strong bake hardening and aging effect. Dual phase (DP) and complex phase (CP) steels have been investigated to examine the effect of thermal and mechanical processing parameters on local properties. For this purpose, two methods have been used to achieve local strengthening, namely local deformation (LD) and local heat treatment (LHT). The local deformation by means of embossing with defined pre-strains leads to enhanced hardness and strengthening. A subsequent aging treatment results in a further increase in mechanical properties. Finally, a local laser heat treatment leads to an increase of hardness and strength and to local strengthening of the material. Local aging on the adjusted strength could be confirmed as well as the stability of the local strengthening.

RIASSUNTO

La ricerca riguarda i processi che portano al rafforzamento locale negli acciai a multifase, che sono caratterizzati da buona formabilità, snervamento continuo, elevata resistenza e da un effetto pronunciato di bake hardening e di invecchiamento. Sono stati studiati gli acciai "dual phase" (DP) e quelli a fase complessa (CP) per esaminare l'effetto delle variabili termiche e meccaniche di processo sulle proprietà locali. A questo scopo, sono stati usati due metodi per avere il rafforzamento locale, cioè deformazione locale (LD) e trattamento termico locale (LHT). La deformazione locale, effettuata mediante intaglio con pre-deformazione definita, porta all'aumento della durezza e del rafforzamento. Un trattamento di invecchiamento successivo aumenta ulteriormente le proprietà meccaniche. Infine un trattamento locale mediante laser aumenta la durezza, la resistenza e porta ad un rafforzamento locale dell'acciaio. L'invecchiamento e la stabilità del rafforzamento locale vengono confermati.

KEYWORDS

Multiphase steels, local deformation, local heat treatment, aging effect and local strengthening

INTRODUCTION

Structures consist of connected nodal and/or surface elements, organized in a way to follow the force path, aiming on the minimization of the selected material. Currently, structural elements are mainly produced using homogeneous materials, materials of different quality or size (e.g. tailored blanks) or even composites. The next step is to adapt not only the geometry to the strain, but also to trim the material itself as much as possible to correspond to its requirements. This can be attained by targeted use of the aging effect.
The aging of steel is a process where the mechanical properties of the material change over time. A well known and used effect is the bake hardening (BH) effect being used to increase the strength of a finished part by means of a heat treatment. BH is a strengthening mechanism which exploits the controlled diffusion of interstitial atoms to pin dislocations, thereby raising the yield strength of the material [1-3]. Special qualities had been developed for sheet application in the automotive industry.
The aging of special steel qualities is technically used in advanced high strength steels (AHSS), where e.g. the increase in strength is realized in the final heat treatment [4]. Own previous investigations showed that the AHSS have a strong aging effect, being much stronger than for conventional BH steels [5-8]. This property provides new possibilities for designing structural components which, for example, can be used in the automotive industry. By means of targeted local deformation (LD) together with subsequent thermal treatment it is possible to obtain a well-defined local behaviour. On the other hand, graded strength behaviour can be produced by a local, limited thermal treatment. For example, the application of a laser beam is one of the possibilities to locally influence and adjust the properties of metals.
The investigations are part of a comprehensive project within the collaborative research centre SFB 675 "Creation of high strength metallic structures and joints by setting up scaled local material properties". The goals of the project are to investigate the effect of the local influence and to develop processes which are able to induce a locally restricted strengthening effect for multiphase steels. The potential and efficiency of different methods and procedures of local forming and heat treatment have to be determined and optimized. The realization of local effects with final global heating processes is of special interest for industrial applications, because these processes can often be integrated in already existing production processes.

MATERIAL

The hot-rolled dual phase steel (DP-W 600) and complex phase steel (CP-W 1000) have been investigated. For these multiphase steels, the standard prEN 10336 is used. The approximate chemical composition and the code of prEN 10336 of the materials are given in Table 1.

Table 1: Chemical composition (wt-%) of the steels investigated and thickness of the sheet material

Material	prEN 10336	C	Al	Mn	Si	Cr+Mo	P	Nb+Ti	Thickness [mm]
DP-W 600	HDT580X	0.08	0.04	1.02	0.06	0.42	0.02	0.03	1.9
CP-W 1000	HDT980C	0.16	0.04	1.92	0.64	0.35	0.01	0.12	2.0

EXPERIMENT

Two different methods were investigated to achieve local strengthening. For the first method the sheet is deformed partially and afterwards heated globally. For this study, an embossing machine was already available to induce local strengthening. The embossing machine (Fig. 1) provides the option of rolling straight or curved contours into the sheet to affect the behaviour of structural elements or components within a definite size and shape by means of a LD, causing an increase in dislocation density.
The sheet is clamped onto a plate, which is movable in longitudinal direction. An arm with a deformation role, moveable around its axis and in transversal direction, is mounted above the plate.
The arm transmits the hydraulic forces to a deformation roll. The embossing depth, the hydraulic force as well as the movement of the arm are computer-controlled. Table 2 lists some specific data of the machine.

Table 2: Specific data of the embossing machine

Max. sheet area	[mm]	1100 x 600
Min./Max. force of roll	[kN]	1 - 300
Max. deformation speed	[mm/s]	18
Roll diameter	[mm]	350

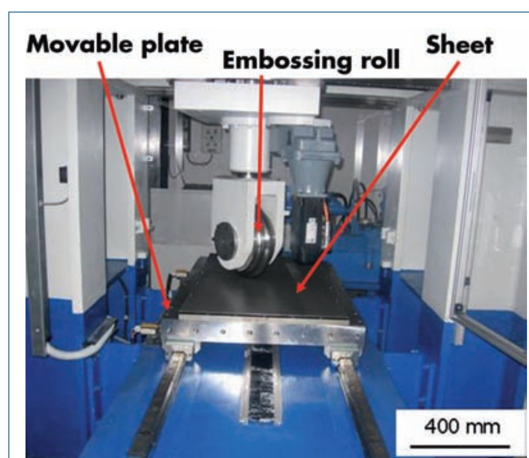

Fig. 1: Embossing machine for locally deformation of sheets.

The production of a defined deformation is made possible by setting the embossing depth. Table 3 shows the specified embossing depths and their

corresponding true strains for the selected materials. The sheets were deformed locally with the specific deformations and then subsequently aged at different temperatures (100°C, 170°C and 240°C) for a holding time of 20 min following the conditions of liquering processes in the automotive industry.
A second method is to deform the sheet globally with defined degrees of deformation.
Consequently, the deformed sheet is heat treated locally by laser. The local laser heat treating (LHT) is accomplished using the laser-remote-welding equipment in the Laser Centre Hanover e.V. in the context of cooperation within the SFB 675. To understand the dependencies, samples of size 500 x 80 x 2.0 mm had been strengthened homogeneously by cold rolling with different thickness reductions (ε = 2%, 5% or 10%) before the LHT. For these tests the laser speed was fixed to 5.0 m/min. The LHT for DP and CP steels was conducted with laser powers between 600 W and 2800 W.
Tensile tests were performed on the samples followed LHT and LD in tension direction using an Instron 250 kN machine. For an initial overview of the expected effects, hardness measurements had been carried out by Omnimet MHT Buehler using a Vickers micro-indenter according to the standard DIN 50133.

RESULTS

LOCAL DEFORMATION BY EMBOSSING

Fig. 2 shows an example of the estimated hardness profiles along the deformation line and in the non-deformed areas as a function of different aging temperatures. The results of hardness obtained for DP-W 600 with the embossing depth of 0.1 mm (true strain = 0.05), following standards for BH material and a holding time of 20 min. The hardness values were determined both in the locally deformed region as well as in the basic sheet. The figure shows an expected increase in hardness of about 20 HV0.1 following LD. Heat treating at 100°C produces no change in the hardness values compared to the initial state. At 170°C, an increase in hardness of about 15 HV0.1 in the locally deformed region was obtained. In addition to this, there was also an increase of hardness in the basic metal at this temperature. A further increase in the aging temperature up to 240°C didn't show a change in the hardness value compared to that at 170°C.
Fig. 3 presents the average data of mechanical properties for the DP-steel with respect to the prestrain (φ) and the aging temperature. For mechanical testing three samples per test were used. The yield and tensile strength values rose steeply as the pre-strain increased to φ = 0.1, while the total elongation decreased with increasing pre-strain as expected. This observation is valid for all aging conditions, without aging and with aging at different temperatures. The influence of the aging temperature in general can be described as to rapidly increase the strength values at higher aging temperatures (170°C and 240°C), while at lower aging temperature (100°C) only a slight increase, which is more significant for the tensile strength at higher pre-strain rates, can be observed. Total elongation decreased with increasing the aging temperature.

Table 3: Embossing depths and corresponding true strains

Embossing depth	[mm]	0.05	0.35	0.50	1.00
True strain φ	[-]	0.05	0.02	0.10	0.15

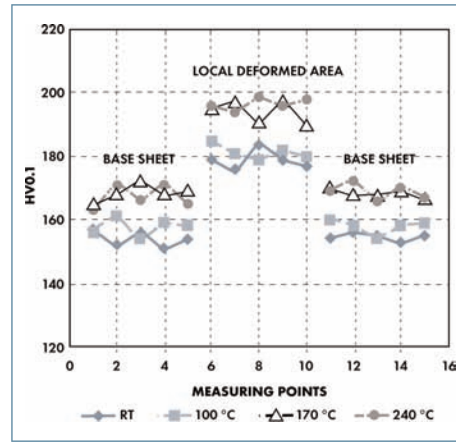

Fig. 2: Hardness values of DP-W 600 in the bottom of the locally deformed region (middle) and in the base material (left and right) followed by an aging treatment for 20 min. Deformation in bottom of embossing: φ = 0.05.

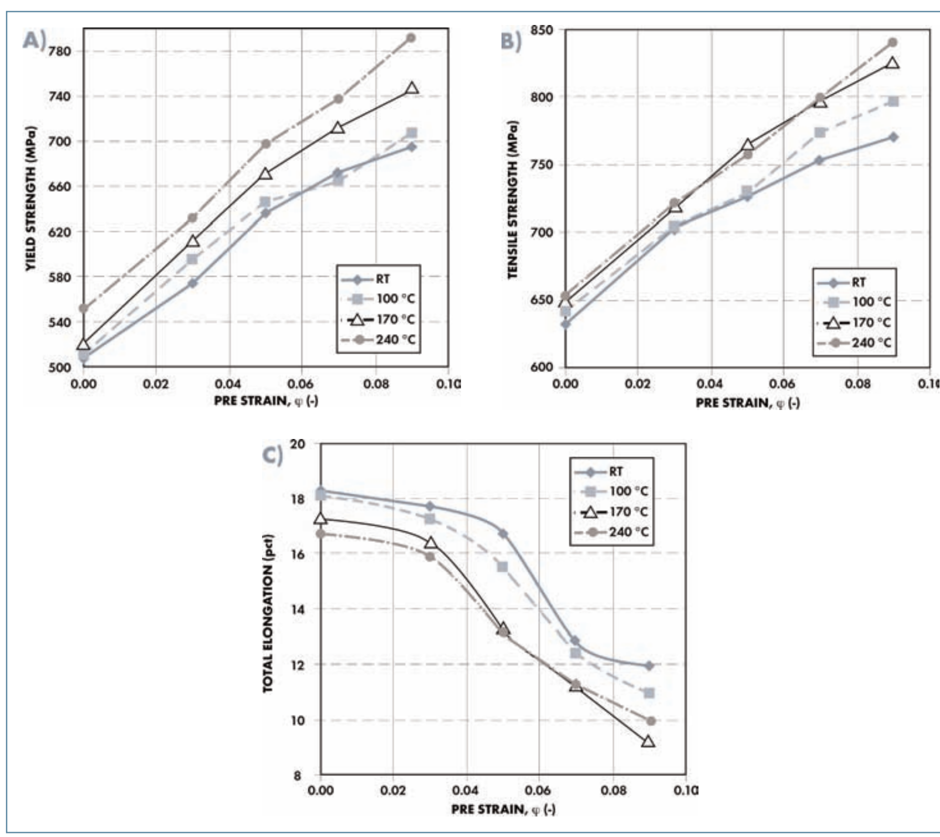

Fig. 3: Mechanical properties of DP-steel after local embossing at different degrees of pre-strain (φ) and global aging treatment at different temperatures, holding time: 20 min.

LOCAL LASER HEAT TREATMENT (LHT)

The hardness distribution for DP-W 600 following a global deformation by cold rolling to $\varepsilon = 5\%$, and a laser treatment with different laser powers at constant laser speed is presented in Fig. 4. After cold rolling the measured hardness was 235 ± 8 HV0.5. For a laser power of 0.6 kW and 1.4 kW a minor increase in hardness could be observed. For a laser power of 2.2 kW, the highest hardness increase of 135 ± 9 HV0.5 and, consequently, local strengthening was measured. For 2.8 kW, a significant hardness increase of 120 ± 11 HV0.5 could be observed. Compared to 2.2 kW the hardness distribution decreased in the middle of laser treated region. This is due to an overheating effect. The reason for the enhancement of the hardness values of samples, which were treated with lower laser powers, compared to the non-laser treated condition, could be contributed to the bake hardening effect. The significantly higher hardness values at higher powers are due to affecting of microstructure. The higher heat treating temperatures lead to the formation of a large number of martensite and bainite with local plastic zones, having a high dislocation density, in polygonal ferrite and local strengthening due to phase transformation [9,10]. This conclusion was confirmed by their microstructures using LOM and TEM [11]. Similar hardness distributions could be measured for DP-steels with $\varepsilon = 2\%$ and 10% [12].

Additionally, the hardness HV0.5 over cross section of samples in the laser track zone was measured in order to show the difference in strengthening in different areas. Fig. 5 shows as an example the distribution of hardness and microstructure in that cross section for DP steel with $\varepsilon = 5\%$. The sheet was heat treated with a laser power of 2 kW at a speed of 5 m/min leading to a maximal temperature of approx. 1000°C at the surface. The change of hardness correlates to the change of microstructure in the heat influenced zone. The maximum of hardness of about 345 ± 6 HV0.5 was observed in the top line of the sheet (position 1), which consisted of martensite and bainite phase. The hardness decreases in the transition zone (position 2) about 50 HV0.5. In this zone lath martensite, bainite and ferrite phase could be detected. In the position 3

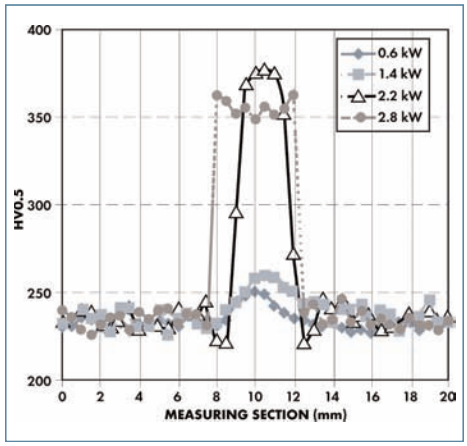

Fig. 4: Hardness distribution of DP-steel, homogeneously cold rolled ($\varepsilon = 5\%$), after laser treatment with different laser powers, laser speed: 5 m/min.

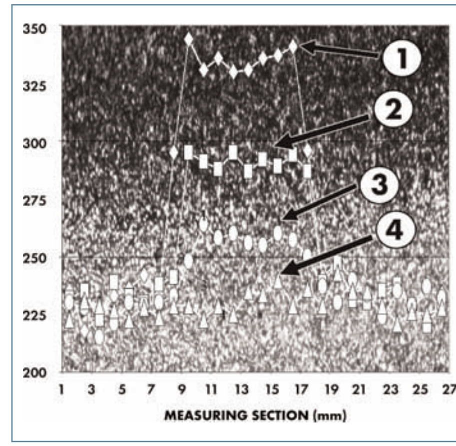

Fig. 5: Micro hardness profile (over the cross-sectional plane) of laser-hardened DP steel ($\varepsilon = 5\%$), laser power: 2 kW and laser speed: 5 m/min.

a hardness level of 256 ± 5 HV0.5 was measured, showing a large number of ferrite, less bainite and a small number of martensite. The hardness values in the position 4 are identical to that in the base metal. Thus, this part of present research demonstrates clearly the gradient effect of laser treatment and the possibility to influence microstructure more or less strongly, depending on the parameters used.

To investigate the changes in the mechanical properties through LHT and to show the stiffening effect of this treatment, tensile tests were carried out additionally. For detecting local flow behaviour the optical measuring system ARAMIS, GOM, was used. Fig. 6 shows the strain distribution of a tensile sample before necking for a DP-W 600, globally pre-deformed with $\varepsilon = 5\%$ by cold rolling and laser treated with 2.8 kW, 5 m/min. The intensive hardening in the heat treated zone is significant. A clear different behaviour and local strengthening could be shown. In tension test local laser treatment leads to strengthening of steel and therewith reduced deformation in these areas, as can be seen in Fig. 6, where necking occurs in the non-treated areas. The treated areas show a strong reduced deformation compared to the non treated areas. The partial heat treatment with the laser leads to a reduced deformation in the

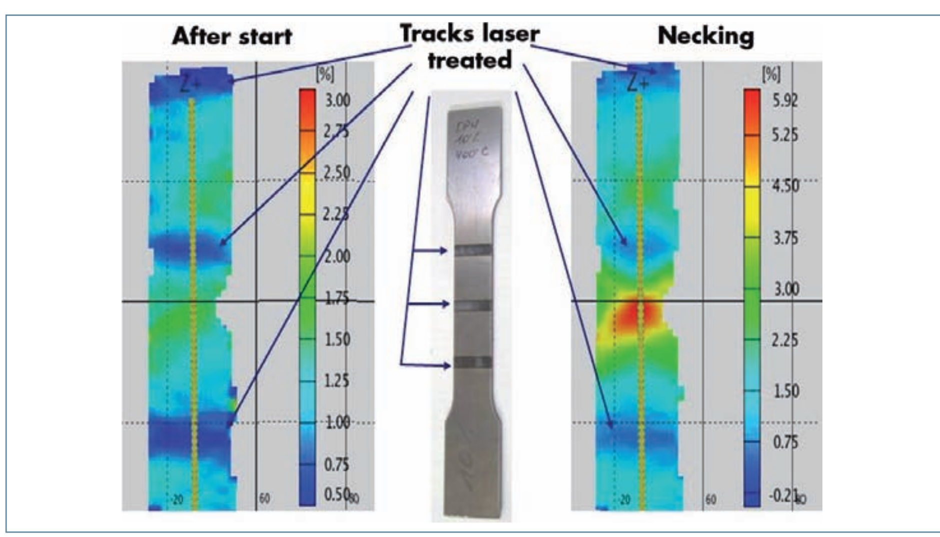

Fig. 6: Local strengthening by laser in DP-W 600, cold rolled with $\varepsilon = 5\%$, laser treated, laser power: 2.8 kW and laser speed: 5 m/min.

tensile test and can be used for local reinforcement.

LONG TIME STABILITY OF LOCAL TREATMENT

Structural components of multiphase steels normally show a natural aging behaviour. The questions to be answered now concern both the stability of the local aging by means of this natural aging process as well as the long-term behaviour of the non-treated regions. In particular, it has to be examined to what extent the local influences can be stabilized and used to improve the material properties of the entire construction unit.
According to the literature, samples of DP and CP steels were aged for several days at a temperature of 70°C [12-14]. As an example, as a result Fig. 7 shows the measured hardness HV0.5 for DPW 600, pre-strained by cold rolling with $\varepsilon = 10\%$, partially laser treated with a laser power of 2.2 kW and a laser speed of 5m/min. The samples were naturally aged at 70°C for long time from 1 up to 9 weeks. Following the aging treatment in a furnace at a temperature of 70°C, a minor change of hardness in the heat treated zone could be observed. In the non affected zone, an increase about 10 HV0.5 could be measured over time. For these investigation parameters, the locally adjusted strengthening effect can be stated to be stable! This aging stability could be also established for DPW 600 and CP-W 1000 subject to changing of pre-strain and laser power.

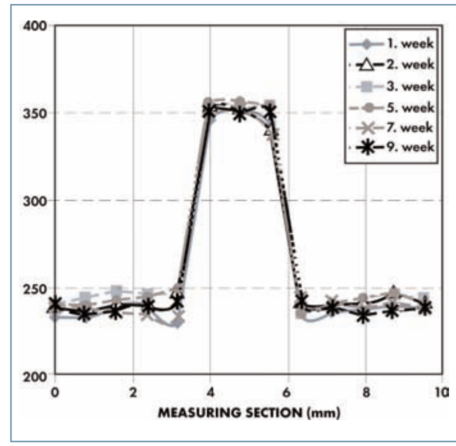

Fig. 7: Long-term aging of laser treated DP-W 600, pre-deformed (ε = 10%) and locally laser treated, laser power: 2.2 kW and laser speed: 5 m/min.

CONCLUSIONS

The possibility for setting-up scaled local material properties in multiphase steels being characterized by good formability, continuous yielding, high strength and a strong bake hardening effect was introduced. The material and experimental procedure as well as two methods to achieve the locally restricted strengthening effect - LD and LHT - were presented. Furthermore, the results of the local adjusted material properties and aging were discussed.
An increase in hardness and strengthening following local deformation through embossing resulted from work hardening. An aging treatment at temperatures between 170°C and 240°C led to a further enhancement of the mechanical properties. It could be demonstrated by hardness measurements and tensile tests that LHT can be used to increase strength partially, depending on the parameters used and that there is a quite wide process window. On the other hand overheating effects occur in case of extended laser exposure or too high laser power, leading to a reduction of strength from the maximum. Tensile tests with locally heat treated areas verified these results showing maximal deformation and failure in the non-treated fields. This research demonstrated that LHT can affect the microstructure of samples to a specific depth from the surface and produce improve local properties by means of higher hardness values, strength and residual compressive stresses.
Partial strengthening seems to open a new field of application for such multiphase steels. The local strengthening of sheet metal materials represents the modification of an existing process. Here the possibility exists to influence only relevant areas, thus representing a method for energy saving. By adjusting the treatment temperature the process can easily be optimized. The relevant areas can also be treated as required by omitting the temperature sensible segments.

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