LOCAL LASER HEAT TREATMENT OF ULTRA HIGH STRENGTH STEELS TO IMPROVE FORMABILITY

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ABSTRACT

Ultra high strength steels are of enormous interest especially in the automotive industry due to their potential in realising light weight structures and improving the crash behaviour. However the poor formability of these steels limits their application for many parts in the car body. A solution to this limitation can be a local heat treatment using a laser beam to soften the material where a high formability is needed. Laser treatment was performed using a Nd:YAG laser with 3 kW maximum power. The output power was temperature controlled to achieve a constant temperature level during the heat treatment. Large areas were treated by scanning the surface with the laser beam. The materials under investigation are dual phase (DP), retained austenite (RA) and martensitic (MS) steels with a tensile strength of 600-1200 MPa. The thickness of the sheets was 1.5 mm. Depending on material and process parameters tempering of martensite, formation of ferrite and transformation of retained austenite are observed as a result of the heat treatment. The changes in microstructure are accompanied by a reduction in yield and tensile strength. Deep drawing of a mock-up geometry reveal a reduction in slide force.

KEYWORDS

Laser heat treatment, UHSS, softening, microstructure, mechanical properties, deep drawing

INTRODUCTION

The need of the automotive industry to combine fuel saving with increased safety of vehicles led to the development of Ultra High Strength Steels (UHSS) [1,2]. Their high yield and tensile strength (fig. 1) enable a reduction in sheet thickness (weight saving) and at the same time keeping or even improving the crash behaviour (safety). The mechanical properties are determined by the microstructure which contains one ore more of the phases martensite, ferrite, retained austenite and carbides. Depending on the nature of the phases and their volume fraction a tensile strength from 600 to 1400 MPa can be achieved. The desired microstructure is achieved by micro-alloying and thermo-mechanical treatment. The use of such steels has led to a compact car body - known as the ULSAB study - with a significant reduction in weight (933 kg) and fuel consumption (4.4 l/100 km) [3].

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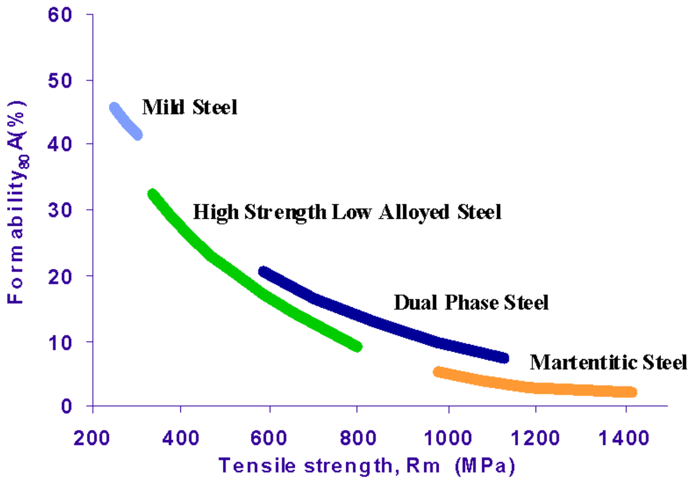

Fig. 1: Formability as a function of tensile strength for various groups of steels

However, a disadvantage of UHSS is the reduced formability compared to typical deep drawing steels which results in a reduced deformation degree, increased spring back and tool wear. A suitable heat treatment of the whole sheet will improve the formability but the high strength will be lost. A solution might be a local heat treatment to improve plastic flow in regions where high deformation degrees are needed. The rest of the sheet is unaffected and in the heat treated regions the high strength is regained by work hardening.

The benefits of laser heat treatment on the formability has already been demonstrated for aluminium alloys [4, 5]. One of the first investigations on local heat treatment of steels using lasers are reported by Bergmann [6]. Among other alloys a dual phase steel (DP 500), a retained austenite steel (TRIP 800, now known as RA 800) and a complex phase steel (CP 1000) were treated. The heat treatment was conducted in a temperature range of 100-1000 °C. None of the steels reveal a significant reduction in tensile strength. For DP 500 even an increase in strength is observed. An explanation for this behaviour is not given. In [7, 8] laser heat treatment and induction heat treatment on sheets of DP steels with a tensile strength between 1000 and 1400 MPa were conducted. Tensile tests reveal that there is a significant reduction in yield and tensile strength. For the steel DP 1400 the yield strength is lowered from 1200 MPa to 700 MPa. At the same time the ultimate strain increases from 8 to almost 20 %. The reason for this behaviour is due to tempering of martensite and formation of ferrite. Limiting dome height tests showed that the deep drawing capacity is improved.

This paper will report on local laser heat treatment of DP, MS and RA steels and the investigations on microstructure and mechanical properties.

1. MATERIALS

The materials under investigation are listed in table 1. The microstructure of the steels is a result of micro alloying and a complex heat treatment. The microstructure of DP steels consists of martensite and ferrite. RA steels contain ferrite, martensite and additionally a certain amount of retained austenite which transforms into martensite during plastic deformation. MS steels are fully martensitic which gives them the highest yield strength of all UHS steels. The various steels were provided as not galvanised sheets (hot or cold rolled) with a thickness of 1.5 mm.

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Tab. 1: Investigated UHS steels

Material	**Rolling condition**	**Microstructure**	**Yield strength (MPa)**	**Tensile strength (MPa)**	**Elongation A80 (%) min.**
DP 600	cold	ferrite + martensite	350-450	600-700	16
DP 1000	cold	ferrite + martensite	700-950	1000-1200	5
MS-W 1200	hot	martensite	950-1200	1200-1400	4
RA-K 700	cold	ferrite, retained austenite, martensite	400-500	700-800	20

2. EXPERIMENTAL WORK

The laser heat treatment (LHT) was conducted with a fiber coupled 3 kW Nd:YAG laser. The processing head is shown in fig. 2a. It contains the collimator and the focussing optic and several sensors for process control (fig. 2b).

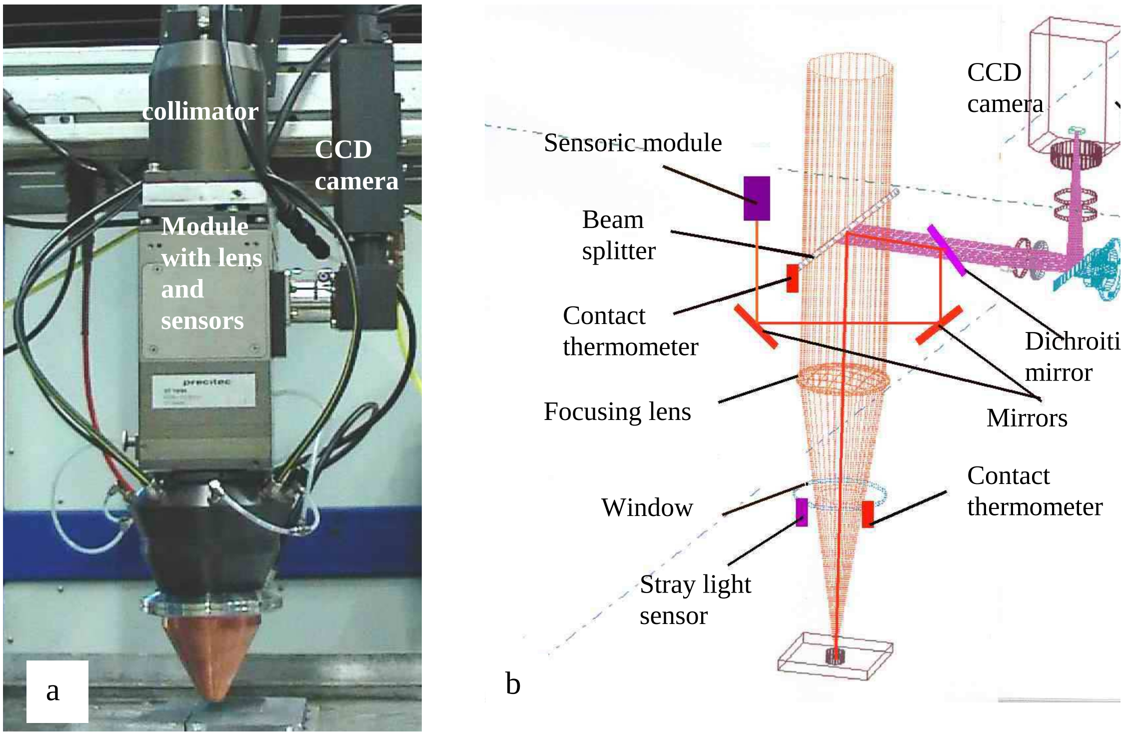

Figure 2: a) Processing head for laser heat treatment, b) beam path inside the processing head

Due to the expected distortion during heat treatment the sheets have to be clamped.
Fig. 3 shows the clamping device for sheets with a size of 200 x 300 mm^2. The diameter of the laser beam on the surface of the sheet is approx. 17 mm. Larger areas are treated by scanning the surface

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with an overlap of 50 %. The main parameters for the laser heat treatment are listed in table 2. The heat treatment was conduced with a constant surface temperature controlled by a pyrometer. The set value for the process control is voltage. To assign this signal to a temperature a set of experiments was conducted in which the temperature was measured with a thermocouple fixed at the back side of the sheet.

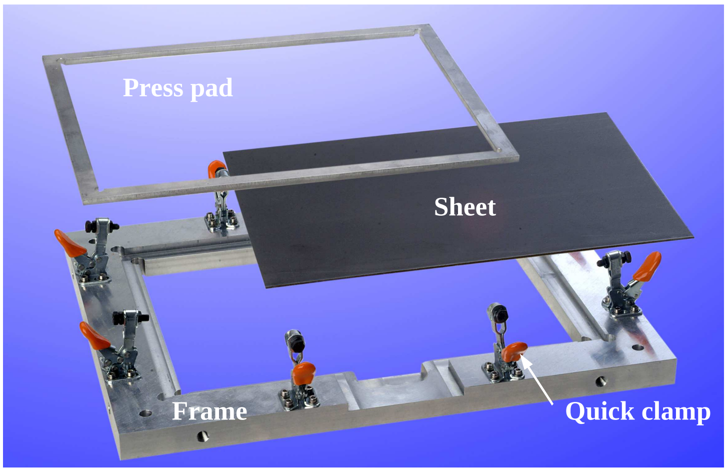

Fig. 3: Clamping device for the steel sheets

Tab. 2: Parameters for laser heat treatment

Parameter	**Range**
Laser power (P)	500 – 3000 W
Temperature (T)	550 – 800 °C
Diameter of laser beam on work piece (d_b)	approx. 17 mm
Velocity (v)	1 m/min
Overlap of single tracks (Δy)	50 %

Fig. 4a shows the laser heat treatment. Since LHT was conducted in air the surface is oxidised (fig. 4b). Due to the inhomogeneous heating the sheets are distorted.

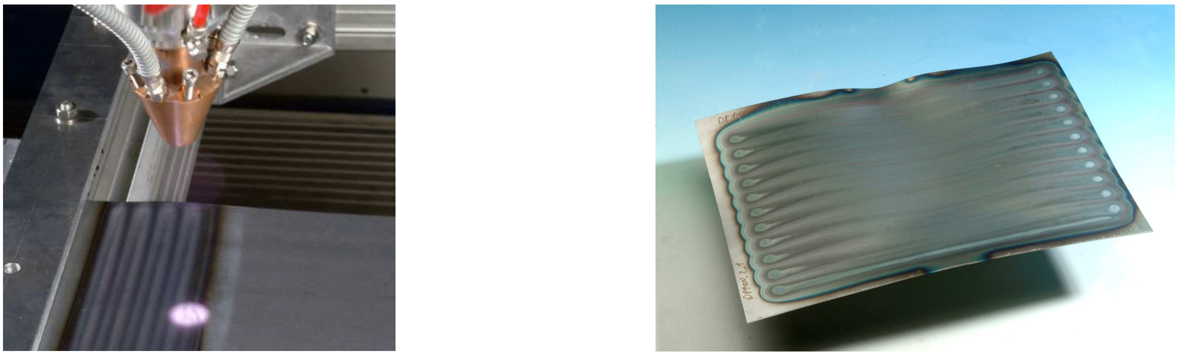

Fig. 4: a) Process of laser heat treatment b) laser heat treated sheet (DP 1000, d = 1.5 mm)

After LHT the microstructure of the sheets was investigated by optical microscopy. The hardness was measured using a Vickers micro indentor. To evaluate the effects on mechanical properties tensile tests were conducted and finally a mock-up part was deep drawn accompanied by FE simulation.

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2. RESULTS AND DISCUSSSION

2.1 MICROSTRUCTURE AND HARDNESS

Fig. 5 shows micrographs of DP 600 before and after LHT at a temperature around 650 °C. The different etching behaviour of the martensite indicates that LHT leads to tempering of martensite. Since the amount of martensite is low the reduction in hardness from 210-230 HV0.1 to 180-190 HV0.1 is small. A similar effect on microstructure and hardness is observed for DP 1000 (290-300 HV0.1 to 240-250 HV0.1). The microstructure of RA-K is shown in fig. 6.

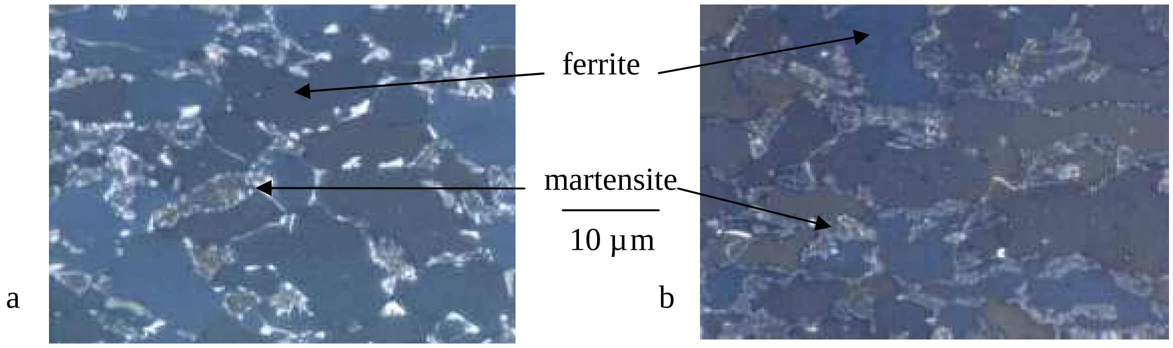

Fig.: 5: DP 600 before (a) and after laser heat treatment (b), max. temperature around 650 °C
a) ferrite**,** b) ferrite + tempered martensite

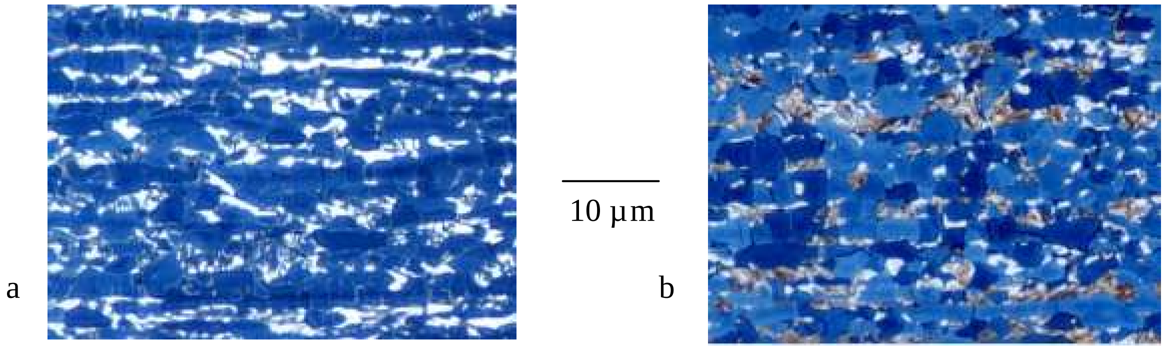

Fig. 6: RA-K before (a) and after laser heat treatment (b), max. temperature around 700 °C
a) ferrite (blue) + retained austenite (12 %) + small amount of martensite
b) ferrite (blue) + martensite + retained austenite (8.5 %)

The initial microstructure contains ferrite and a high amount of retained austenite (12 %). Some amount of martensite is also detected. It should be noted that austenite and martensite cannot be clearly distinguished from each other in the micrograph. The austenite content was measured by x-ray diffraction. During LHT at a temperature around 700 °C stress relaxation occurs and one third of the metastable austenite transforms into martensite. LHT has no effect on the hardness which is around 250 HV0.1 before and after the treatment. Fig. 7 shows micrographs of MS-W 1200. The initial microstructure is almost fully martensitic. A small amount of ferrite and bainite can be found. LHT at a temperature around 650 °C leads to tempering which causes a reduction in hardness from 420-430 HV0.1 to 350-380 HV0.1. Increasing the max. temperature around A_{c3} leads to a significant increase in the volume fraction of ferrite. This indicates that a transformation from martensite to austenite (heating) and austenite to ferrite (cooling) has taken place. The hardness is

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reduced to a value around 270 HV0.1. A further increase of the max. temperature leads to a more coarse structure of bainite, martensite and ferrite. This indicates that a higher amount of the initial microstructure has transformed into austenite during heating. The hardness lies also in the range of 270 HV0.1.

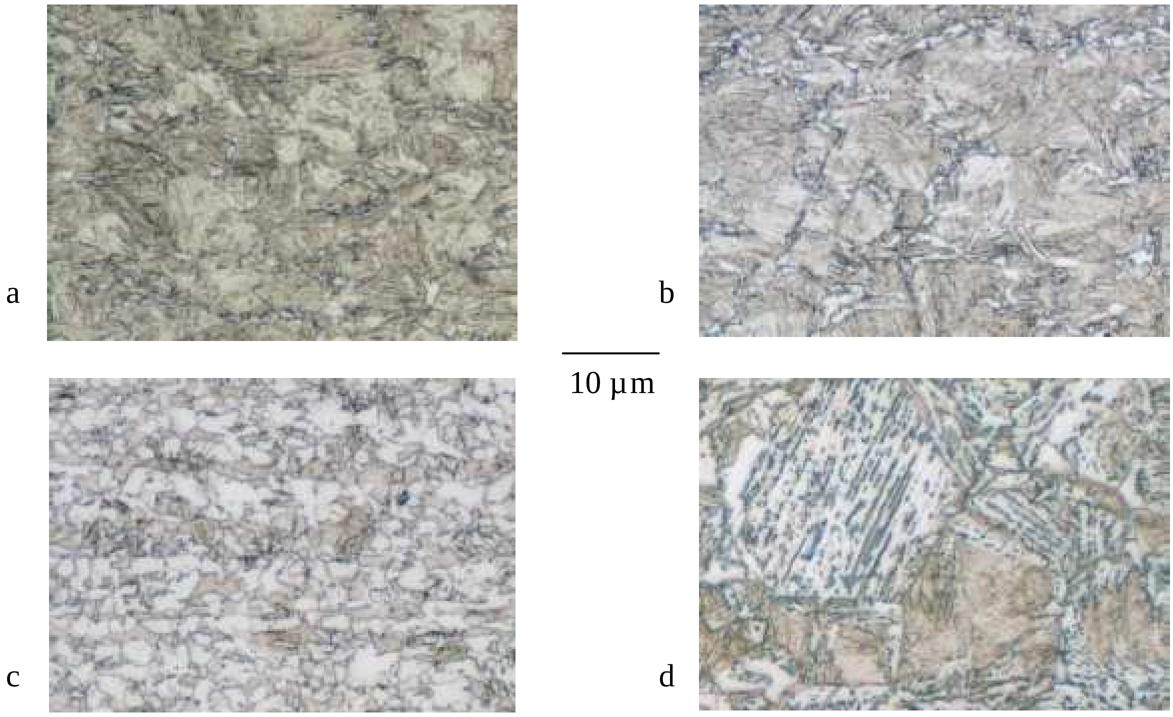

Fig. 7: MS-W before (a) and after laser heat treatment (b-d)
a) martensite, small amount of bainite and ferrite, 420-430 HV0.1
b) martensite, bainite and ferrite (temp. ≈ 600 °C), 350-380 HV0.1
c) martensite and ferrite (temp. ≈ 700 °C), 260-280 HV0.1
d) martensite, ferrite and bainite (temp. ≈ 800 °C), 260-280 HV0.1

3. MECHANICAL PROPERTIES

3.1 TENSILE TESTS

The tensile test samples were cut from fully heat treated sheets. The samples were cut at angles of 0 °, 45 ° and 90 ° to the rolling direction. However, the range of the values indicate no anisotropic behaviour. Table 3 shows yield strength, tensile strength and elongation for the investigated steels. DP 600, DP 1000 and MS-W 1200 reveal a significant reduction in yield and tensile strength and an increase in elongation after LHT. For the DP steels this can be attributed to the softening of martensite (tempering) whereas the effect in MS-W 1200 is caused additionally by the formation of ferrite. The later is mainly responsible for the increase in strain. This is illustrated by the stress-strain-curves in fig. 8. At a max. temperature around 600 °C yield and tensile strength are reduced significantly but not elongation. Plastic flow is still restricted due to the fact that the microstructure contains mainly martensite (see fig. 7b). At a higher max. temperature during LHT the ductile phase ferrite is formed (see fig. 7c) leading to a further decrease in strength but mainly to an increase in elongation. The effect of LHT on RA-K 700 is different from the other steels. Yield and tensile strength are reduced only slightly as well as elongation. According to the microstructure (fig. 6) this can be attributed to the transformation of retained austenite during LHT. The benefit of retained

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austenite is that it improves plastic strain and additionally – since it is transformed to martensite during plastic flow – improves strength. Therefore a reduction in the volume fraction of retained austenite will result in softening as well as reduced plastic flow. Generally it can be concluded that for DP 600, DP 1000 and MS-W 1200 an increased formability can be expected from LHT. For RA-K 700 at least a reduction in slide forces might be the benefit of LHT. Considering complex forming operations with a high deformation degree LHT might be not beneficial.

Tab. 3: Best results of tensile testing for various steels (values are average values for test samples cut at angles of 0 °, 45 ° and 90 ° to the rolling direction)

Material	**Yield strength (MPa ± 20)**		**Tensile strength (MPa ± 20)**		**Elongation A80 (% ± 2)**	
	Untreated	LHT	Untreated	LHT	Untreated	LHT
DP 600	460	394	707	498	8.3	26
DP 1000	618	478	1016	716	9.6	17.4
RA-W	610	540	750	680	27	21
MS-W 1200	1186	628	1429	850	4.4	10.8

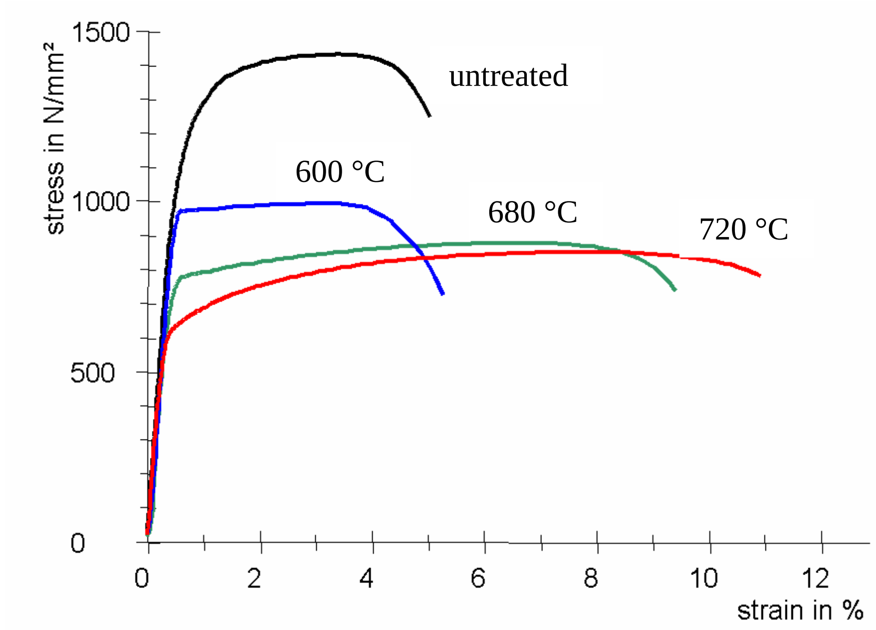

Fig. 8: Stress-Strain-Curves for MS-W 1200 (d = 1.5 mm)

3.2 DEEP DRAWING TESTS

The tensile tests reveal promising effects of LHT on the formability for the materials DP 600, DP 1000 and MS-W 1200. However, the tensile test simulates an uniaxial stress condition whereas forming operations e.g. for car body components are more complex. Therefore forming tests are necessary to evaluate the effect on deformation behaviour as well as on forming forces. The mock-ups geometry used in this work for the first forming tests is shown in fig. 9. In a first step the areas which undergo the highest deformation were projected onto the sheet (fig. 9). In a second step a CNC program for LHT was generated from this data.

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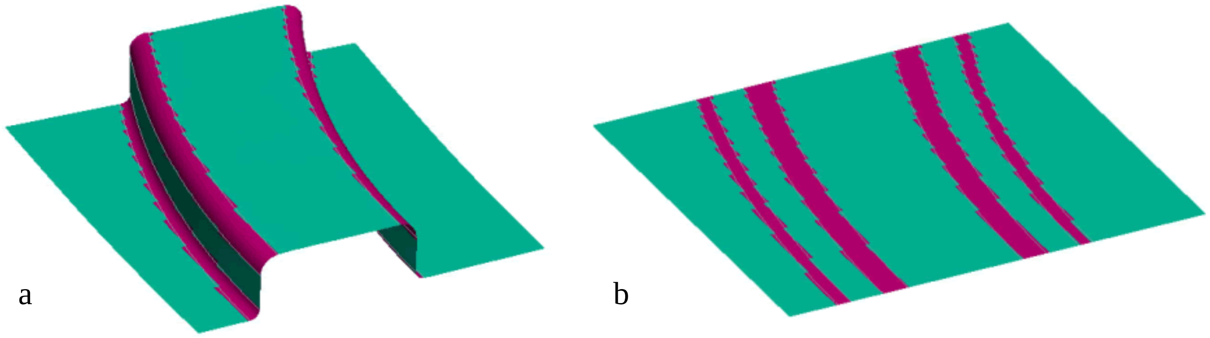

Fig. 9: Mock-up geometry for deep drawing experiments with areas of highest deformation marked (a) and projection of tracks to be laser heat treated onto the sheet (b)

Parallel to the experimental work FE simulation of the deep drawing process was conducted to estimate the effect of LHT on the forming operation. The sheet was segmented into areas with different mechanical properties according to fig. 9. The values for the mechanical properties of the LHT zones were taken from the tensile tests. Fig. 10 show the calculated slide forces for an untreated and laser heat treated sheet. It can be clearly seen that the forces are significantly reduced in the regions where LHT was conducted.

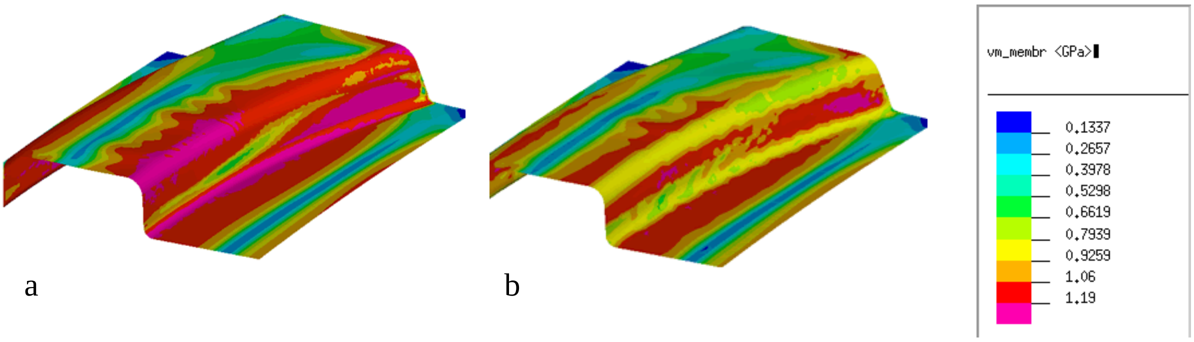

Fig. 10: Calculated slide forces for an untreated (a) and a laser heat treated sheet (b) of MS-W 1200

The first forming tests using MS-W 1200 (fig. 11) confirm the results of the simulation. For a laser heat treated sheet the slide force is reduced to 78 % of the value for an untreated sheet at the maximum draw depth of 40 mm. Forming the same mock-up with RA-K 700 led to a reduction of the slide force in a similar range (18 %). For this special forming operation the beneficial effect of the lower yield strength is superimposing the loss in ductility caused by the lower volume fraction of retained austenite.

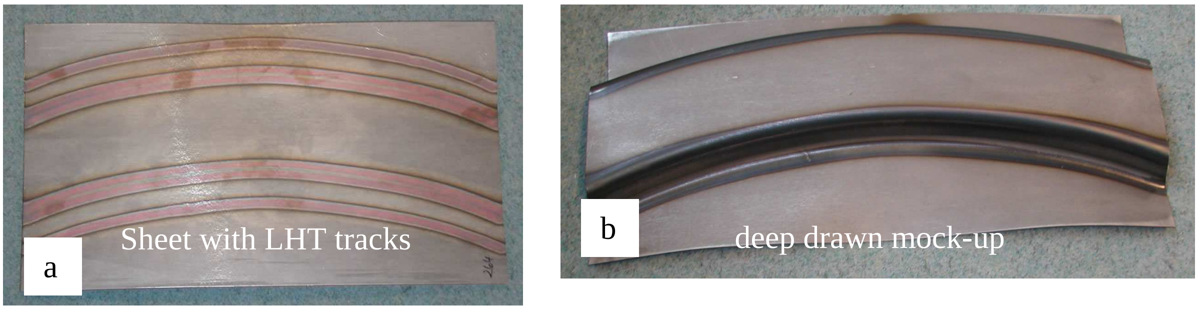

Fig. 11: Deep drawing of MS-W 1200; a) laser heat treated sheet (d = 1.5 mm) b) formed mock-up; slide force for a draw depth of 40 mm (F_N = 240 kN): untreated: 1300 kN, LHT: 1020 kN, reduction in force: 22 %

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3. CONCLUSIONS AND FUTURE WORK

The main conclusions of this work on laser heat treatment of ultra high strength steels are:

Laser heat treatment has the potential to improve formability of UHS steels.

Tensile tests of DP 600, DP 1000 and MS-W 1200 reveal a significant reduction in yield and tensile strength and an increase in elongation after LHT. The effect is due to tempering of martensite and in the case of MS-W also due to an increase in volume fraction of ferrite.

Tensile tests of RA-K 700 reveal a minor reduction in yield and tensile strength and a decrease in elongation. This can be attributed to the lower content of retained austenite which has transformed into martensite during LHT. From this result it can be expected that LHT is not beneficial for high deformation degrees.

Deep drawing of a mock-up geometry using MS-W 1200 and RA-K 700 showed a significant decrease in slide force (≈ 20 %) compared to the initial condition.

FE simulation can help to identify the regions where a softening is needed and can predict the effect on the slide forces.

Future work will be concerned with the following tasks:

Reduction of distortion by investigating various strategies for the laser heat treatment.

LHT of galvanised sheets.

Investigations on spring back after LHT.

Forming experiments of more complex geometries.

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