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Quasi-simultaneous local hardness reduction via remote laser scanner for cost-effective mechanical joining of press-hardened high-strength steel 22MnB5

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Abstract

The diversification of materials is an effective way to decrease car body weight and CO_2 emission of modern automobiles. Hot stamped steel structures are already broadly used because of their high strength and significant weight reduction potential. In order to create multi material car bodies mechanical joining technics such as clinching and self-pierce riveting are used since they allow bimetallic joints in combination with adhesives. However, the joinability by clinching and self-pierce riveting of high-strength steels such as 22MnB5 in the press-hardened state is limited due to the tremendous hardness. A thermal hardness reduction in the joint area enables the production of multi-material joints including martensitic high-strength steels with classical joining technologies, as it is investigated thoroughly by others. The produced joints showed sufficient load-bearing capabilities for automotive applications, but the present heat treatment strategies cannot be implemented in industrial production chains economically due to their long cycle times.
In this paper an innovative approach is presented to decrease the process time of the local heat treatment using a Remote Laser Scanner. It is proposed to irradiate several joint areas periodically by a high power laser source. Furthermore, it is proposed that the fast periodic energy input leads to a hardness reduction of the joint areas quasi-simultaneously and therefore decreases the overall process time drastically. In this paper the process is described more detailed and the results of feasibility studies are presented.

Keywords: Remote Laser Scanner; heat treatment; press-hardned steel; mechanical joingin; automotive

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1. Introduction

Press-hardened high-strength steels such as 22MnB5 are already widely used in modern car bodies. In the press-hardened state they have ultimate tensile strengths up to 1500 MPa and because of that they are used especially in crash-relevant parts such as B-pillars. The usage of high strength steels leads to a decrease in car body weight and CO_2 emissions. In order to exploit the advanced mechanical properties of the press-hardened high-strength steels further, an improvement of joining technologies is necessary. In particular mechanical joining techniques such as clinching and self-pierce riveting offer the possibility of weight reduction in multi material car bodies. Mechanical joining of steels like 22MnB5 in the press-hardened state requires new joining methods as presented by Meschut and Janzen, 2014. One of these approaches includes a local heat treatment of the joint area prior to conventional mechanical joining. Different heat sources for the local conditioning are investigated and multi material joints are realized successfully. Using a laser for local heat treatments offers high process flexibility. Nevertheless, an industrial implementation of this joining technique is hindered by the large process times necessary for the solid phase transformation and hardness reduction. Although, hardness of circa 310 HV can be achieved in less than one second in a squared area of 400 mm², a more drastic hardness reduction (200-250HV) in an equally large area is not realized in less than 30 s. (Bergweiler, 2013; Meschut et al., 2014)

In this paper a Remote Laser Scanner is used to locally reduce the hardness of the press-hardened high-strength steel 22MnB5 by annealing. First, parameters for slight hardness reduction (around 300 HV) are identified. Secondly, a highly innovative and time-saving approach for a quasi-simultaneous hardness reduction is presented.

2. Experimental approach

2.1. Material

The investigated steel is 22MnB5 in the press-hardened state with a mean hardness of 495 ± 7. The 1.8 mm thick sheets are coated with aluminum-silica. For the experiments samples of the size of 125 mm in length and 40 mm in width are laser cut out of larger sheet material. Up to five areas are treated by the laser in the middle of the sample and at least 20 mm apart from each other.

2.2. Experimental set up and measurement methods

As heat source for the hardness reduction the diode-pumped disk laser TruDisk 5001 with a maximum output of 5000 W is used (Yb:YAG; $\lambda = 1030$ nm). To deflect the beam the Remote Laser Scanner PFO 3D by Trumpf is used ($f = 450$ mm; $z_r = 13.3$ mm; $w_0 = 0.325$ mm). The defocusing of the beam is realized by positioning the PFO 3D with a CNC-gantry system along the Z axis. The theoretical spot diameter D is calculated according to Equation (1).

$$D(z) = 2w_0 \cdot \sqrt{1+\left(\frac{z}{z_R}\right)^2} \tag{1}$$

The areas are cut through the center of the treated area, embedded and polished for Vickers hardness measurements. HV2 indentations are made 0.5 mm away from the upper and bottom side creating two hardness profiles across the heat treated area as illustrated in Fig. 1.

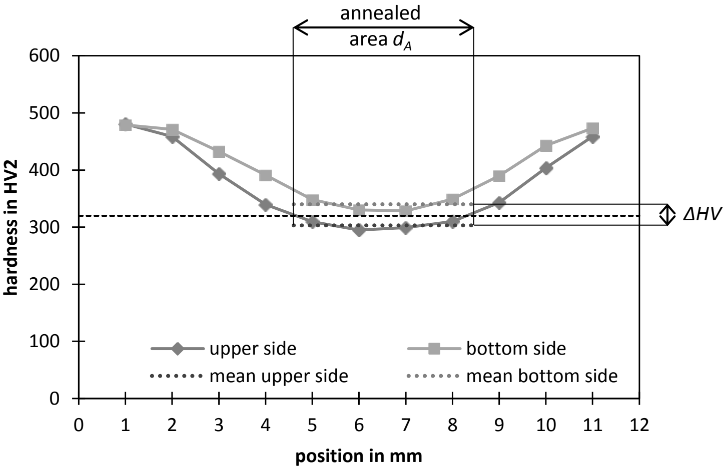

Fig. 1. Hardness profile and mean hardness for upper and bottom side with d_A and ΔHV (P = 1000 W; D = 10 mm; t_P = 0.5 s)

The annealed area is defined as the area in which the hardness falls below the threshold value of 320 HV2 at the upper side of the sheet and is described with the diameter d_A. The mean hardness in this area is used to describe the hardness reduction. In case the hardness does not fall below the threshold, the minimum hardness at the upper side is used. In order to evaluate the annealing depth the difference between the mean hardness ΔHV at the bottom and upper side in the annealed area is calculated as illustrated in Fig. 1.

2.3. Experiments

The hardness of the martensitic steel can be reduced through annealing below A_{c1}, normalizing or a brief austenitization above A_{c3} directly followed by annealing below A_{c1}. During normalizing the cooling velocity has to be controlled (< 27 K s^{-1}) in order to prevent martensite formation. With that strategy hardness below 200 HV can be achieved, because it results in a soft ferrite and perlite structure. Although the lowest hardness can be maintained, this strategy is not suitable for industrial application because the slow cooling is achieved through a continuously degrading heat input and very long process time. With a short austenitization directly followed by annealing the total process time is reduced to 30 s for hardness around 250 HV. Annealing below A_{c1} offers the fastest hardness reduction in less than a second but so far no hardness in the treated area below 300 HV is reported. (Meschut, et al., 2014)

In this paper parameters for annealing with a Remote Laser Scanner are identified in order to achieve the maximum hardness reduction in less than a second. The varied process parameters are listed in

Table 1. The spot diameter D is held constant at 10 mm.

Table 1. Parameters to identify optimal intensity for given pulse time

pulse time t_P in s	laser power in W	spot diameter D in mm
0.25	1400 - 2000	10
0.50	800 - 1200	10
0.75	600 - 900	10
1.00	450 - 700	10

In order to increase the annealed area the spot diameter D is increased by further defocusing, see Equation (1). The laser power is adjusted in order to maintain the beforehand identified optimal intensity. The process parameters are listed in Table 2.

Table 2. Parameters to increase the annealed area

pulse time t_P in s	laser power in W	spot diameter D in mm
0.50	1000 - 2250	10 - 15
0.75	750 - 1687	10 - 15

For further hardness reduction longer annealing times are necessary. Quasi-simultaneous annealing is an approach to reduce the process time per area for hardness reduction below 300 HV. An area is irradiated by the laser with a short pulse for the time t_P. After the time t_C the same area is irradiated with another pulse. During the time t_C the laser irradiates N other areas in the same way. Therefore, each area experiences a periodic heat input. The principle is illustrated in Fig. 2. In order to prevent the temperature to rise above A_{c1} during the repeated heat input, the laser power is lowered for each pulse leading to the process strategy shown in Table 3. Spot diameter D is constant 15 mm and pulse time t_P is also constant 0.5 s.

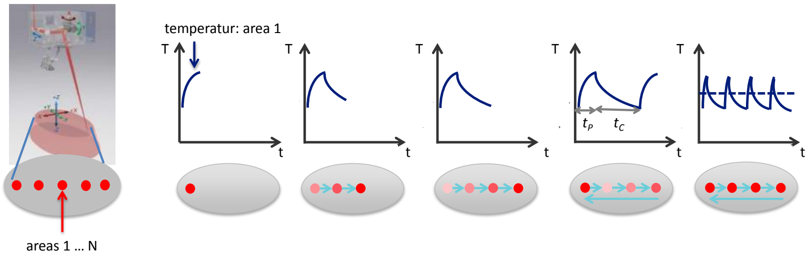

Fig. 2. Principle of quasi-simultaneous annealing with a Remote Laser Scanner

Table 3. Parameters during quasi-simultaneous annealing

number of pulses	laser power in W
1	2250
2	1380
3	1125
4-5	900
5-18	788

Equation (2) describes how many areas can be processed simultaneously as a function of the time the laser spot needs for the distance between two areas t_J and the times t_P and t_C.

$$N = \frac{t_C}{t_P + 2t_J} + 1 \tag{2}$$

With t_C = 3 s; t_P = 0.5 s and t_J = 50 ms a total of 6 areas could be processed quasi-simultaneously.

3. Results and discussion

3.1. Process parameter for annealing: influence of pulse time

Fig. 3 (a) summarizes the results of the first experiments described in Table 1. The general trend is illustrated by connecting the data points. With increasing laser power the hardness decreases until a minimum. Further increase of the laser power results in re-hardening in the middle of the annealed area as illustrated in Fig. 3 (b). The re-hardening occurs first at the upper side which leads to a negative *ΔHV.* The laser is a superficial heat source with Gaussian intensity profile and increases the temperature above A_{C3} first in the center of the annealed area where austenite is formed. Upon cooling the austenite transforms into martensitic structures which leads to the increase of hardness. (Meschut et al., 2014)

Fig. 3. (a) Hardness reduction and hardness difference *ΔHV* as function of laser power (b) re-hardening in the center of the annealed area (P = 1150 W; D = 10 mm; t_P = 0.5 s)

The annealing processes which lead to a hardness reduction to circa 300 HV2 seem to occur already during 0.25 s. A further increase of pulse time up to 1 s does not lead to lower hardness. Little is still unknown about the effect of short heat treatments with extensive heating and cooling velocities to the microstructural changes in press-hardened 22MnB5 and characterization of the annealed microstructure is still pending. (Gunnarsdóttir, et al., 2016).

ΔHV as well seems unaffected by the pulse time. In contrast the diameter of the annealed area d_A increases with the pulse time, see Fig. 4 (a). In a thin sheet the heat flow along the width and length is larger than along the thickness. Therefore, additional pulse time has a stronger effect on d_A than on *ΔHV*.

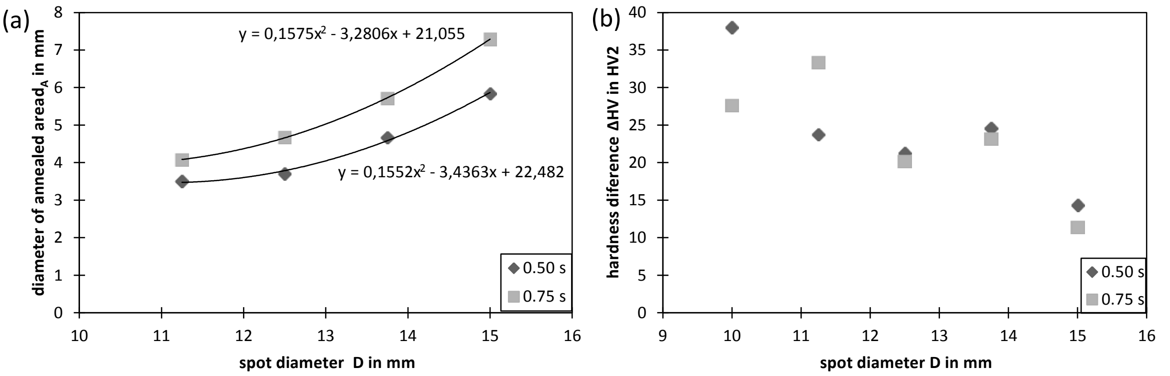

Fig. 4. (a) Diameter of annealed area d_A as a function of spot diameter D with empirical trends (b) ΔHV as a function of spot diameter D

Table 4. Optimal intensity values for minimal hardness depending on pulse time

pulse time t_P in s	optimal intensity in W cm^{-2}	energy per surface area J cm^{-2}	mean hardness in annealed area in HV2
0.25	2292	573	305
0.50	1273	634	303
0.75	955	716	310
1.00	764	764	303

For each pulse time an optimal intensity is identified for which the maximum hardness reduction is observed, see Fig. 4. (a) Diameter of annealed area d_A as a function of spot diameter D with empirical trends (b) ΔHV as a function of spot diameter D

Table 4. Additionally the energy per surface area is calculated as product of intensity and pulse time. This value increases from 573 J cm^{-2} to 764 J cm^{-2} with increasing pulse time, which means that more energy is required to achieve the same hardness reduction when the pulse time increases. A physics-based model to describe the hardness reduction in the annealed area as a function of laser power, pulse time and geometrical values (spot diameter, sheet thickness etc.) has not elaborated yet. Further experiments are necessary to collect additional data.

3.2. Increasing the annealed area

The previous experiments show that the annealed area is much smaller than the spot diameter. For the mechanical joining a soft area of at least 8 mm is necessary. The spot diameter is increased by further defocusing for pulse times 0.5 s and 0.75 s. The results are visualized in Fig. 4. For each pulse time a well-fitting cubic trend curve is identified, see Fig. 4 (a). The maximal spot diameter investigated is 15 mm. For that spot diameter the distance between the sheet and the Remote Laser Scanner is 755 mm. A larger distance is not possible with the current set up due to geometrical restrictions of the CNC-gantry system. Following the postulated empirical trends a spot diameter D of 15.5 mm (for $t_P = 0.75$ s) and 17.2 mm (for $t_P = 0.5$ s) is necessary for an 8 mm large annealed area with hardness below 320 HV2. With the above stated optimal intensity, laser powers of 1800 W and 2970 W, respectively, should result in maximum hardness reduction. With the maximum laser power of 5000 W an annealed area with $d_A = 25.8$ mm and $d_A = 22.4$ mm is possible according to the trends, in case the geometrical restrictions are bypassed. In further experiments the correlation will be evaluated.

The findings prove that the press-hardened steel can be softened to circa 305 HV2 in an area large enough for mechanical joints with single laser pulses of 0.5 s duration. The standard DVS/EFB 3451 for multi-material mechanical joints distinguishes between soft steels with ultimate tensile strength lower than 600 MPa (180 HV (DIN EN ISO 18625)) and high strength steels with ultimate tensile strength above 1000 MPa (320 HV (DIN EN ISO 18625)). For the material combination steel with aluminum clinching and self-pierce riveting are well-suitable for soft steels (< 180 HV), but only clinching is suitable to join high strength steels with aluminum for a limited extent and self-pierce riveting is considered unsuitable for this joint type. (DVS/EFB 3451) However, Meschut, et al. 2014 state that self-pierce riveting of press-hardened steel at the punch side is also possible for hardness of 300 HV. Abe et al., 2012 successfully clinched steel sheets with an ultimate tensile strength of up to 980 MPa (310 HV (DIN EN ISO 18265)) by adapting the clinching process. This advanced clinching process requires a change of die geometry and new clinching machines.

The presented annealing heat treatment enables the possibility to join aluminum with press-hardened steel through an additional but considerable short process step. So far conventional clinching and self-pierce riveting of aluminum (EN AW 6181A-T4) and heat treated 22MnB5 is achieved only after brief austenitization directly followed by annealing for 30 s (Meschut et al., 2014). This additional process time is not suitable for cost-effective automotive mass production and a new approach of quasi-simultaneous annealing is formulated.

3.3. Quasi-simultaneously annealing

Joint areas are periodically exposed to the laser beam according to the pulse strategy described in Table 3 for up to 18 times. There is no significant improvement of hardness reduction observable. The size of the annealed area increases from 5.8 mm to 8.0 mm and the hardness is circa 14 HV2 lower after 18 pulses than for one pulse. An increase in process time from 0.5 s to 10.54 s per area resulting in a 14 HV2 larger hardness reduction does not seem reasonable. The effect is rather small since the power for subsequent pulses is estimated based on optical assessment of the glowing area. Most likely the heat input is not high enough to maintain the necessary annealing temperature of approximately 700°C during all pulses. Further tests will be conducted with thermal control via thermography and thermocouples.

In a subsequent trial areas are heated by a laser beam for 2 and 3 times respectively with the parameters listed in Table 5. After a fourth such pulse re-hardening is observed.

Table 5. Parameters for quasi-simultaneous annealing

pulse time t_P in s	time between pulses t_C in s	laser power in W	spot diameter D in mm
0.50	15	2250	15

The hardness in the annealed area is illustrated as function of number of pulses in Fig. 5 (a). With the second pulse the hardness is reduced by 10 HV2 compared to a single pulse. The third pulse resulted in a 6 HV2 decline of hardness. A similar trend is observed for d_A. After 3 pulses d_A increased from initial 5.8 mm (one pulse) to 9.3 mm.

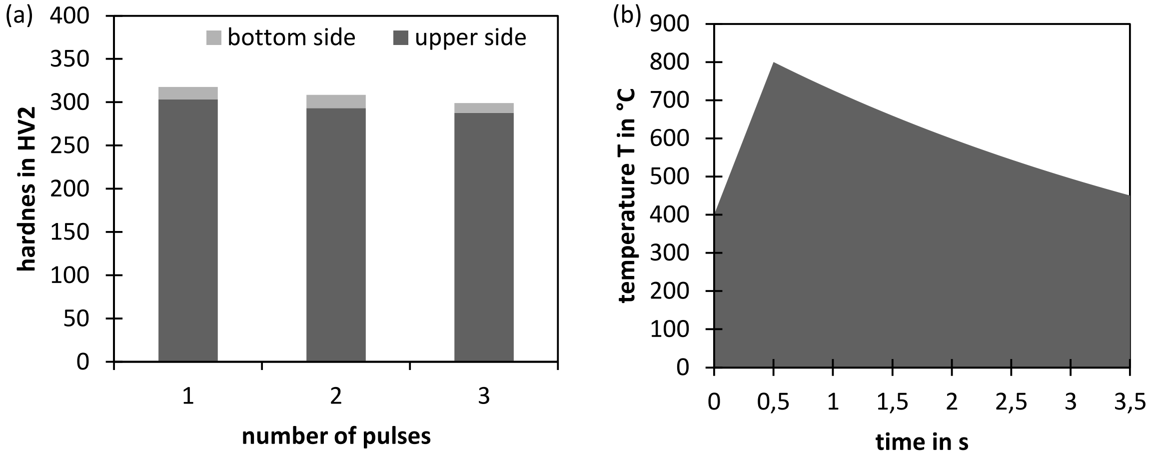

Fig. 5. (a) Hardness at upper and bottom side as function of number of pulses with parameters seen in Table 5, (b) simplified temperature change during one pulse (t_P = 0.5 s, t_C = 3 s)

In further tests the parameters in Table 3 will be adjusted to higher laser powers to increase the annealing temperature and enhance the effect of multiple laser pulses. In addition austenitization directly followed by quasi-simultaneous annealing will be investigated. The first pulse could heat the material above A_{c3} and cause formation of austenite. The second pulse prevents the temperature of falling below M_s, which is approximately 400°C (Bergweiler, 2013) and further pulses would lead to annealing of the metastable austenite below A_{c1}. Meschut, et al., 2014 achieve hardness below 250 HV with continuous annealing at 600°C for 30 s directly after brief austenitization at approximately 900°C. Temperature measurements indicate that the sheet temperature falls by approximately 300°C during 3 s after laser exposure in the range of 800°C (Bergweiler, 2013; Meschut et al. 2014; Gunnarsdóttir and Basurto, 2015).

For a first simple approximation of the mean temperature during one pulse, it is assumed that the temperature rises linearly from 500°C to 800°C during the pulse time 0.5 s and then falls exponentially according to Equation (3) in the following 3 s (T_A = 800°C, T_U = 25°C, k = 0,2).

$$T = T_U + (T_A - T_U) \cdot e^{-kt} \tag{3}$$

The resulting temperature curve is illustrated in Fig. 5 (b). Based on that simplification the mean temperature during one pulse can be estimated to be 606°C during one pulse and the following 3 s cooling time. Nine of such cumulative pulses would expose the material for approximately 31.5 s to a temperature of 606°C. It can be expected, that the resulting hardness reduction is comparable to the effect of a continuous annealing for 30 s at 600°C. The hardness reduction could be enhanced by a previous austenitization as described before. This approach still has to be confirmed in experiments. In theory hardness lower than 250 HV2 in 5.25 s per area is possible. The confirmation of this theoretical approach requires a closed-looped coaxial temperature control in combination with a Remote Laser Scanner. Such a system is not available yet, but will be developed at the iLAS.

4. Conclusions

In this research study several strategies are investigated in order to optimize the process time for lowering the hardness of press-hardened steel before mechanical joining. It is shown, that the hardness can be lowered until 305 HV2 in an area with the diameter of 8 mm in 0.75 s using a Remote Laser Scanner. Additionally, evidence is presented that even larger areas can be prepared for mechanical joining in 0.5 s using a Remote Laser Scanner and a 5000 W laser source. Further the theoretical background of quasi-simultaneous annealing is described. The evaluation of this approach is the focus of further experiments.

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