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Laser welding of HCT980XD at subzero temperatures to improve heat affected zone material properties

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Abstract

The ultrahigh strength dual-phase steel HCT 980 XD is a commonly used material for automotive body parts. The excellent material properties result from a ferritic-bainitic matrix with embedded areas of martensite. When fusion welded, however, this brings the disadvantage of softening in the heat affected zone (HAZ), which leads to crack initiation there during tensile tests. The state of the art research of laser welding of these steel grades suggests that there is no possibility to cope with the strength and hardness drop in the HAZ. One possibility to improve the material characteristics is to increase the heat dissipation out of the workpiece. Therefore, a clamping device was designed which completely consists of copper, to improve heat dissipation. A continuous nitrogen gas flow suppresses condensation of moisture in the air to prevent the formation of ice because of falling below the dew point. This experimental setup allows to carry out welding trials at subzero temperatures of down to - 100 °C
Preliminary laser welding experiments conducted at - 90°C showed that it is possible to almost double the strain with an occurring crack in base metal during tensile tests. The cause for this change in material behavior is an alteration of microstructure in the HAZ, when welding trials which were carried out at room temperature are compared to trials welded at -90 °C.
As – 90°C is not a suitable temperature for industrial applications, further trials were conducted to determine the minimum temperature required to achieve the improved material behavior.

Keywords: Laser; HCT980XD; subzero temperatures; heat affected zone;

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1. Introduction

To reduce the consumption of resources and fuel and, furthermore, to decrease CO_2-emissions, lightweight design takes an important role in automotive design. But it must be achieved without affecting safety relevant parts. A common method for decreasing the weight of body in white (BIW) structures while preserving full safety standards is using ultrahigh and advanced high strength steels. Thereby a weight of up to 17 – 43 % can be saved as it was stated by Aurélien in 2008. Therefore, they are usually used for safety relevant body parts such as A-pillar, B-pillar, roof rails, longitudinal beams etc. and the market keeps growing.

As an example, galvanized HCT 980 was designed as a material for the automotive sector. Its great advantage is a high ultimate strength of $R_m = 980 – 1130$ MPa combined with an adequate formability at room temperature because of a possible elongation at break of $A_{80} = 10$ % (Salzgitter booklet 2017). The material properties are adjusted upon the rolling process by heating them in a continuous furnace where subcritical temperatures of below Ac_3 are applied. At these temperatures, ferrite remains mostly stable while carbides are transformed into austenite. Throughout rapid cooling, a ferritic-martensitic matrix is formed. A higher martensite content leads to higher strength values, Shome 2015. The mechanical behaviour shows a good ratio of yield strength (YS) and ultimate strength (UTS) combined with a good work hardening index. (Salzgitter booklet 2017 and Shome 2015)

As appropriate as the described steel may be as a construction material, there are some issues when it comes to joining. The heat input of each fusion welding process, for example laser welding, harms the elaborately adjusted material properties, which results in a drop of hardness and strength in the heat-affected zone (HAZ). (Farabi 2011 and Parkes 2014) Although advantages of laser beam welding are a high intensity and therefore high welding speeds as well as a low energy input, the effect still occurs.

2. Motivation

In a HCT 980 laser weld, weld seam and coarse grain zone (CGHAZ) reach hardness values above base material level. The point of minimal hardness can be found in the subcritical heat affected zone (SCHAZ) [5] at maximum temperatures directly beneath Ac_1. (Xia 2008 and Biro 2006) Tempering of martensite is considered to be the primary cause of softening, as ferrite is stable at temperatures beneath A_{c1} (723 °C). (Xia 2008 and Ma 2014) The tempering caused by the welding process leads to precipitation of submicroscopic carbides. This effect increases with rising heat input. (Xia 2008 and Dan 2011) Therefore, the martensite fraction decreases, resulting in a softened structure, as was shown by Ma in 2014. Thus, laser welded specimens fail in tensile tests at approximately half the strain of base metal, although strength values remain mainly unchanged. (Saha 2014) This is due to the majority of strain and hence necking being concentrated in the SCHAZ. This leads to a reduction of the total strain and a crack initiation in the SCHAZ. (Xia 2007 and Xu 2012)

As described, softening in a laser welded HAZ is a common phenomenon with ultrahigh strength steels. The martensite fraction is tempered by each heat input.

Therefore, the key to prevent tempering in the SCHAZ of ultrahigh strength steels might be to increase heat dissipation out of the work piece by using an active cooling device. Hamatani showed in 2006, that the proficient welding temperature for ultra-fine grain steels is e.g. - 150°C. It is possible to shift the crack initiation out of the HAZ into the base material when those materials are laser welded at these temperatures.

Laser welding trials at subzero temperatures were performed for the fully martensitic 22MnB5 at temperatures down to -100 °C. But although the drop of hardness presumedly was reduced, no improvement of UTS in tensile tests could be observed. (Gerhards 2016) This effect is most likely connected to the martensite content of 100 %, as the softening degree is directly proportional to the martensite fraction. (Xia 2008)

In the case of dual-phase steels, a minimum time is required to initiate the tempering process. This time is decreased when containing higher martensite fractions. Therefore, applying an active cooling device when laser welding the HCT 980 is promising due to the significantly lower martensite fraction compared to the fully martensitic 22MnB5 steel.

Preliminary tests showed that it is possible to shift the crack initiation in tensile tests from the heat affected zone to base material when laser welding is carried out at temperatures of - 90 °C. Although this proves the working hypothesis, a temperature of -90 °C is roughly application orientated. Therefore, welding trials to determine the maximum temperature needed to achieve a crack initiation in base material must be carried out.

3. Experimental Setup

A clamping device made entirely of copper was designed to achieve cooling temperatures down to - 100 °C. It is cooled by a device which mixes gaseous and liquid nitrogen, leading to a range of temperature between 0 °C and – 155 °C. After cooling the clamping jaws, the gas is lead through nozzles directly to the welding area to suppress the atmosphere and to avoid condensation, Fig. 1.

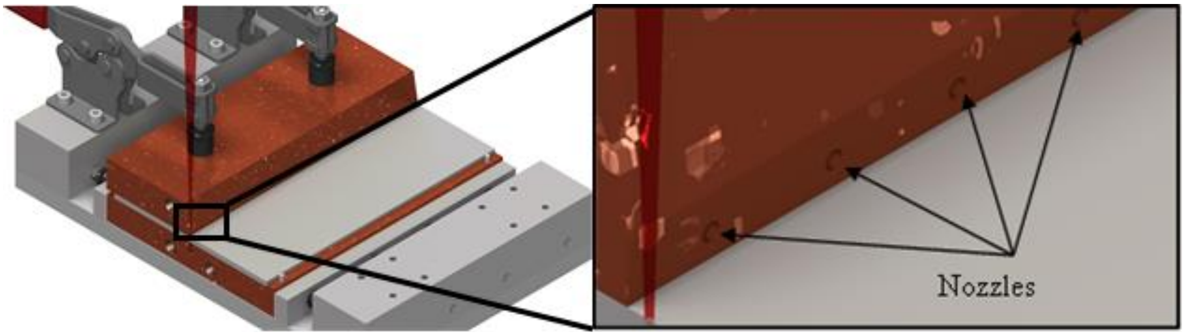

Fig. 1. (a) Clamping device to apply active cooling by using cooled nitrogen gas; (b) Nozzles for nitrogen as shielding gas.

Furthermore, the clamping device is placed in an insulating double walled chamber which shields the clamping device from the atmosphere. A detailed description of this design was presented in the paper of Gerhards in 2016.

All welding trials were carried out with a TruDisk 16002 Disk Laser, a focal diameter of 0,6 mm and a focal length of 400 mm. The standard for the welding trials was SEP 1220 “Testing and Documentation Guideline for the Joinability of Thin Sheets of Steel – Part 3: Laser Beam Welding”. The sheets were at first adjusted in a butt joint and laser power was configured to 4 kW. The welding speed was determined to 7,6 m/min, as at this velocity the sheets were fully welded through. After those trials, additional experiments were carried out where the sheets were adjusted in an overlap joint with 16 mm overlapping width. For this approach, the welding speed was determined to 3,6 m/min

The material was not altered prior to welding, as the zinc coating has no negative effects on the welding process. Only for the overlap trials a gap was adjusted to enable zinc evaporation without having negative effects on the weld seam quality.

As HCT 980 shows isotropic behaviour in rolling direction (Xia 2007), all specimens were taken perpendicular to rolling direction, to display the worst case. As reference, welding trials at room temperature were carried out.

Cross sections were etched using a 2 % Nital etching for light- microscope examinations. To gain a detailed picture of the hardness profiles, micro-hardness (HV 0,1) measurements were carried out. The indentations in the weld seam and in the HAZ were placed in two lines with an offset, so that they are within a linear distance of only 0,05 mm. Tensile tests were carried out using a video extensometer to determine the true strain values.

4. Results and Discussion

Prior to the welding trials at subzero temperatures, a reference weld at room temperature was carried out. A visual inspection after welding showed no obvious defects. This applied also to the cross sections where no cracks, shrinkage cavities or pores were detected. Looking at the hardness measurements, a typical profile can be found, where the hardness in the heat affected zone (HAZ) shows values beneath, and the weld seam shows values above base material level. The point of minimal hardness can be found directly next to the so-called white band, Fig. 2 a. Tensile tests show the typical behaviour as well. While the stress reaches values similar to base material level, the strain is significantly reduced, Fig. 2 b.

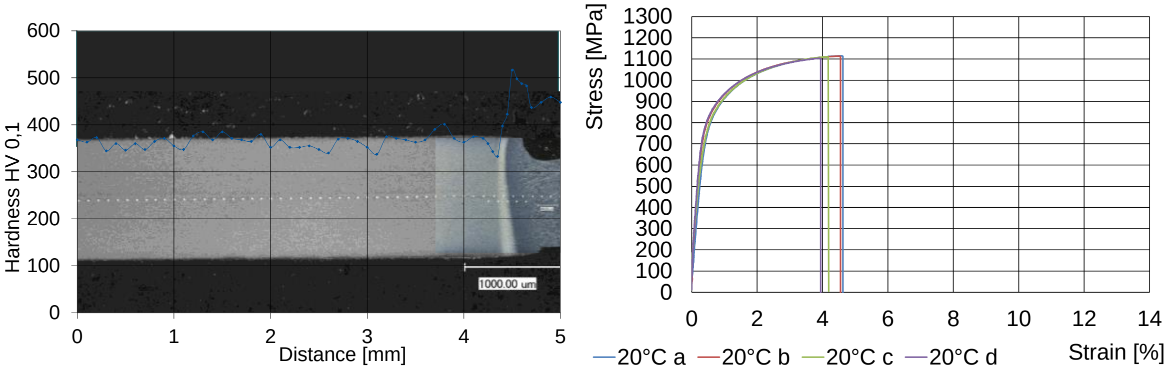

Fig. 2. At room temperature laser welded HCT 980 steel: (a) Hardness measurements; (b) Tensile test

The welding trials carried out at room temperature were followed by trials conducted at subzero temperatures. As mentioned in the chapter Motivation, preliminary tests where the HCT 980 was welded at temperatures of - 90 °C, showed that the crack initiation can be shifted from the HAZ to base material. Stress and strain values are nearly on base material level in this case.

Because welding at - 90 °C is not suitable for industrial application, further trials with rising temperatures were conducted to determine the required temperature to achieve a crack initiation in the base material. The welding trials started at - 90 °C to reproduce the preliminary tests and were conducted in 10 °C steps until the crack initiation could not be found anymore in the base material.

Visual inspections as well as microscopic examinations of cross sections showed no defects such as pores or cracks for all trials. This applies also for hydrogen-related cold cracking which did not occur even if condensation was found on the sheets prior to welding.

All trials showed a similar behaviour until a temperature of - 10 °C was reached. As can be seen in Fig. 3 a, the specimens fail in tensile tests at strain values above 10 %, except for the outlier "- 20°C a", where the crack was initiated through an undercut in the fusion line.

When welding is carried out at - 10 °C, the crack occurs partially in base material and HAZ. This behaviour cannot be linked to undercuts or other discontinuities. Thus, - 20 °C can be marked as turning point for the improvement of HAZ properties in a HCT 980 laser weld.

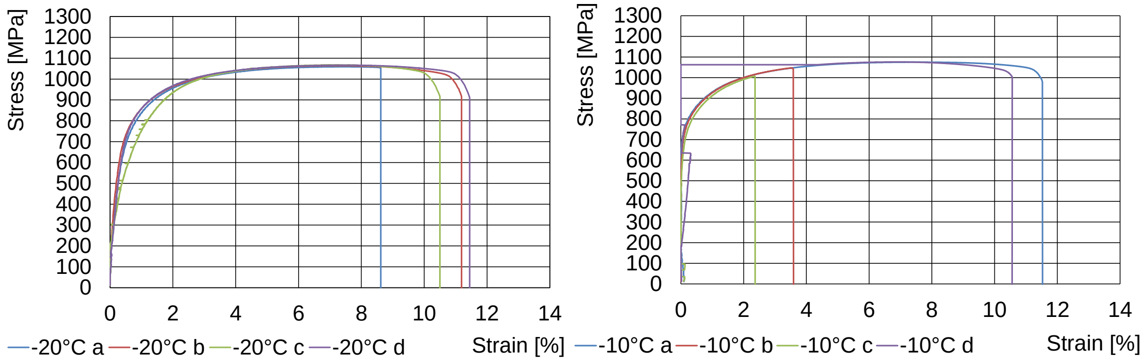

Fig. 3. Tensile tests of HCT 980: (a) Laser welded at - 20 °C; (b) Laser welded at - 10 °C

Looking at the hardness measurements, there seems to be a slight difference between the - 20 °C weld (Fig. 4 a) and the - 10 °C weld (Fig. 4 b). But taking the actual values into account, the minimal hardness is approximately the same (328 HV 0,1 for - 20 °C and 340 HV0,1 for - 10 °C). This also applies to the welding trial carried out at room temperature (333 HV0,1 for 20 °C). It appears that the improvement of HAZ material properties cannot be displayed by the micro hardness, as all hardness values are on a comparable level.

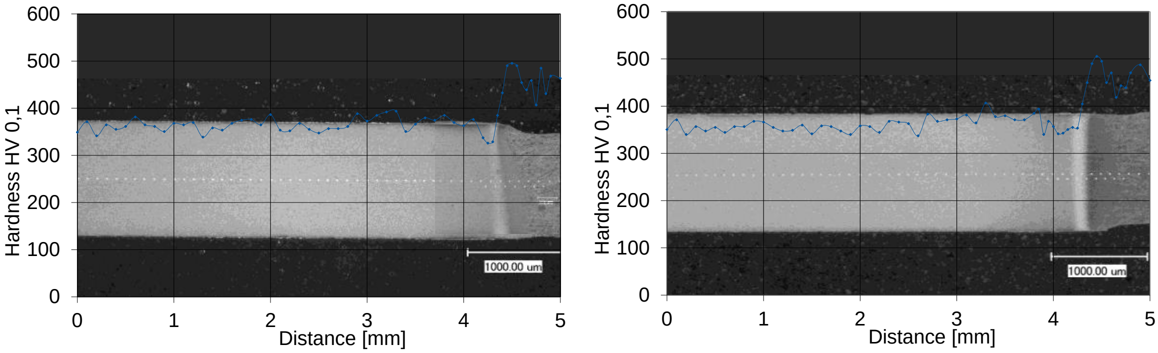

Fig. 4. Laser welded HCT 980 steel: (a) at – 20 °C, Hardness measurements; (b) at – 10 °C, Hardness measurements

The cause for cracking can be found in the local strain values. For the specimens where the crack occurs in HAZ, strain and in the following necking, is obviously concentrated in the soft zone. Therefore, the microstructure there must have higher strain capacities than the microstructure of the specimens where the crack occurs in the base material - although hardness values are on the same level. An EBSD analysis might show the difference between the microstructures. But it has to be taken into account that the different areas of the HAZ are very small and therefore it is challenging to get sufficient data.

The butt weld trials are followed by welding trials in an overlap joint configuration. As the overlap joint is the most commonly used joint configuration for automotive applications, it is of major interest to achieve comparable results for this configuration.

The welding trial was carried out at a temperature of - 20 °C, as this temperature was determined as turning point for an improvement of HCT 980 laser HAZ properties. Like in the case of butt welds, no defects were found, neither in visual inspections, nor in microscopic examinations.

Unfortunately, the tensile shear tests did not show the same results as the tensile tests from the butt welds. The crack initiated within the overlap at significantly lower stress and strain values compared to base material or at room temperature welded specimens taken from butt welds, Fig. 5.

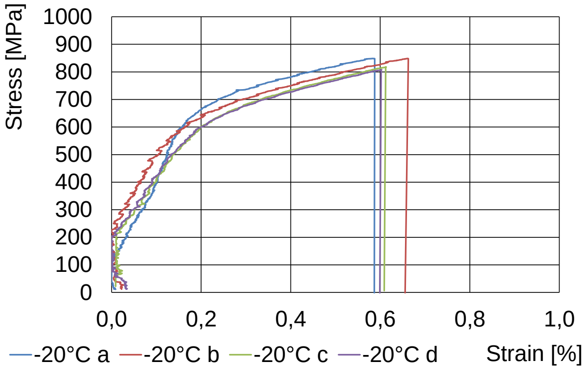

Fig. 5. HCT 980 steel overlap, laser welded at - 20 °C, tensile shear test

The mode of failure was shearing of the weld seam itself. This behaviour is caused by the concentrated tension due to the shear aspect. As the welding trials were carried out according to SEP 1220 "Testing and Documentation Guideline for the Joinability of Thin Sheet of Steel – Part 3: Laser Beam Welding", no further adjustments regarding the focal diameter were made. Regardless, the logical consequence for further research is to increase the virtual weld width to avoid shearing of the weld seam.

5. Summary

Preliminary experiments showed that it is possible to shift crack initiation in tensile tests of a HCT 980 laser butt weld from HAZ to base material when temperatures of -90 °C are applied during welding. As this temperature is far from any industrial application, further experiments were conducted to determine the required minimum temperature to achieve the improvement of the HAZ microstructure.

Welding trials were conducted following SEP 1220 "Testing and Documentation Guideline for the Joinability of Thin Sheet of Steel – Part 3: Laser Beam Welding", where the temperature was increased by 10 °C respectively from a starting temperature of - 90 °C.

An improvement of HAZ material properties with a crack initiation in base material could be found until a temperature of - 20 °C was reached. At - 10 °C, the crack occurred partially in HAZ and partially in base material, thus this temperature could be identified as the turning point.

All specimens which were welded in a temperature range from 20 °C to – 90 °C showed similar hardness values in HAZ. Therefore, the micro hardness tests cannot be used as an indicator for the failure mode. It appears that for the specimens where the crack occurred in the HAZ, strain and necking were concentrated in the soft zone. The microstructure obviously shows higher strain capacities compared to specimens with a crack initiation in base material - although hardness values are on the same level. To determine the difference between the microstructures, EBSD measurements should be carried out.

Additionally, overlap welding trials were conducted. In tensile shear tests, stress and strain values were significantly lower than base material values. This behavior is caused by the concentrated tension due to the shear aspect. Thus, the failure mode was shearing of the weld seam itself. For a further improvement, the virtual weld width would have to be increased.

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References

Aurélien, P.; Múnera D. D.; Schmit F.: Innovative Press Hardened Steel (Usibor 1500P and Ductibor 500P) Based Laser Welded Blanks Solutions for Improved Weight Savings and Crash Safety Management. Verl. Stahleisen (2008).

Biro, E.; Lee, A.: Tensile Properties of Gleeble-Simulated HAZ from Various Dual-Phase Steels. Sheet Metal Welding Conference XII (2006).

DAN, S.; Massardier-Jourdan, V.; Fabregue, D. et.al.: HAZ Microstructures and local mechanical properties of high strength steels resistance spot werlds. ISIJ International Vol. 51 (2011) pp. 99-107.

Farabi, N.; Chen, D.I.; Zhou, Y.: Microstructure and mechanical properties of laser welded dissimilar DP600/DP980 dual-phase steel joints. Journal of Alloys and Compounds (2011), pp. 982 – 989.

Gerhards, B.; Reisgen, U.; Olschok, S.: Laser beam welding of ultrahigh strength martensitic steels with active cooling. JLA 28 (2016).

Hamatani, H.; Miyazaki, Y.; Otani, T., et.al.: Minimization of heat-affected zone size in welded ultra-fine grained steel under cooling by liquid nitrogen during laser welding. Materials Science and Engineering A 426 (2006), pp. 21 – 30.

Ma, J.;Kong, F.; Liu, W. et.al.: Study on the strength and failure modes of laser welded galvanized DP980 steel lap joints. Journal of Materials Processing Technology 214 (2014) pp. 1696-1709.

N.N.: Salzgitter Flachstaht HCT980X (HC600XD, CR590Y980T-DP). (2017).

Parkes, D.; Westerbaan, D.; Nayak, S.S. et.al.: Tensile properties of fiber laser welded joints of high strength low alloy and dual-phase steels at warm and low temperatures. Materials and Design 56 (2014) pp.193-199.

Saha, D.C.; Westerbann, D.; Nayak, S.S. et.al.: Microstructure-properties correlation in fiber laser welding of dual-phase and HSLA steels. Materials Science & Engineering A 607 (2014) 445-453.

Shome, M.; Tumuluru, M.: Introduction to welding and joining of advanced high-strength steels (AHSS). Elsevier Ltd. (2015).

Xia, M.; Biro, E.; Tian, Z.; et.al.: Effects of Heat Input and Martensite on HAZ Softening in Laser Welding of Dual Phase Steels. ISIJ International, Vol. 48 (2008) pp. 809-814.

Xia, M.; Sreenivasan, N.; Lawson, S. et,al.: A comparative Study of Formability of Diode Laser welds in DP980 and HSLA steels. Journal of Engineering Materials and Technology Vol. 129(2007) pp. 446-452.

Xu, W.; Westerbann, D.; Nayak, S.S. et.al.: Microstructure and fatigue performance of single and multiple linear fiber laser welded DP980 dual-phase steel. Materials Science and Engineering A 553 (2012) pp.51-58.