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Joining ultra-high strength steels by edge welds

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Abstract

An advantage of edge welding is the possible reduction in the required flange length compared to conventionally welded lap joints. As part of a pilot study, this method has been applied to welding of a press hardened martensitic chromium steel in similar and dissimilar joints to current high and ultra-high strength steels. A dedicated optical set-up was used to implement these welds. High-frequency beam oscillation was used to ensure mixing of the different materials and to prevent crack formation which appeared mainly in the combination with the ferritic-pearlitic grade. The welding results are evaluated using micrographs, hardness tests and tensile tests. For the tensile testing, an adapted LWF-KS2-sample geometry was designed to generate for the first time reliable comparative results compared to conventionally overlap-welded laser welds.

Keywords: Edge welds; beam weaving; dissimilar joints; mechanical properties

1. Introduction

With view to light-weight construction the approach of welding a the face-side of flanges is a promising approach. Shortening the width contributes to weight reduction as well as a larger cross-section can be achieve by orienting the seam parallel to the plane of the joint. Edge welding offers the possibility of varying the joint cross-section by adjusting the welding depth. Compared to overlap welding, where the seam width is limited by the spot diameter, the joint area between the two joining partners can also be increased by using beam oscillation. The high-frequency beam oscillation also mixes the molten material and can thus help to homogenize the mixed structure in the case of material combinations of dissimilar types.

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2. Experimental set-up

2.1. Welding set-up

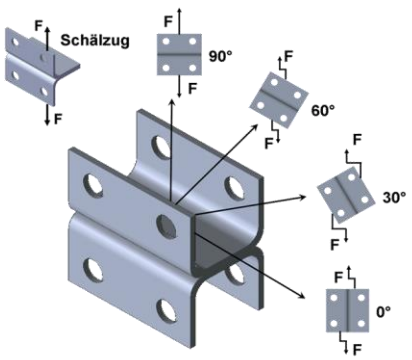
The welding tests were carried out at the application center of the company Scansonic MI. Experiments were performed using an 8 kW disk laser. The laser processing head has a focusing focal length of 500 mm, an aspect ratio of 1 to 2.9 and allows beam oscillation at a frequency of up to 1000 Hz. This can be varied in both the x and y directions. Precise positioning of the processing head is based on the triangulation principle using camera-based edge detection. An optical fiber with a core diameter of 200 µm realizes a focus diameter of 580 µm. This diameter was used in welding with oscillating laser beam. When welding with a static laser beam, a beam diameter of approx. 1 mm was set on the surface by defocusing.

2.2. Assessment

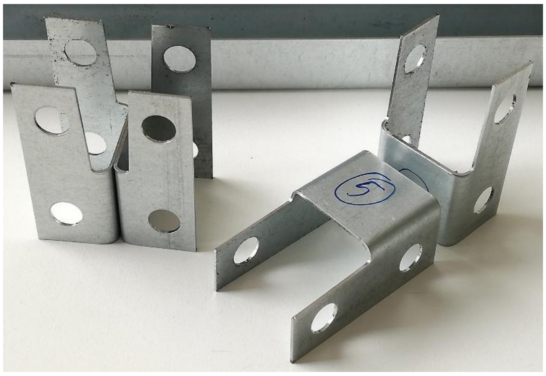
For an assessment of the strength and the effects of the heat of welding hardness tests were conducted by the method of Vickers applying a test load of 1 kp (9.81 N). Indentation were place at the weld centre line and at the middle thickness of the sheets. The drawing in Figure 3a shows the measuring scheme. A rough metallographical analysis was carried out along the hardness measurements in order to find a correspondence between hardness and microstructure.

2.3. Specimens

The parameters were developed at flat sheet material. Any surface coatings were removed prior to welding for testing the material behaviour itself. For mechanical testing a new specimen geometry based on the LWF-KS2 specimen (Figure 1a) was developed. This patter was chosen because of the high stiffness of the specimens as well as due to the easy fit into existing clamping devices.



a) Standard KS2 specimen and definition of the load angles



b) Modified KS2 specimen with cutout

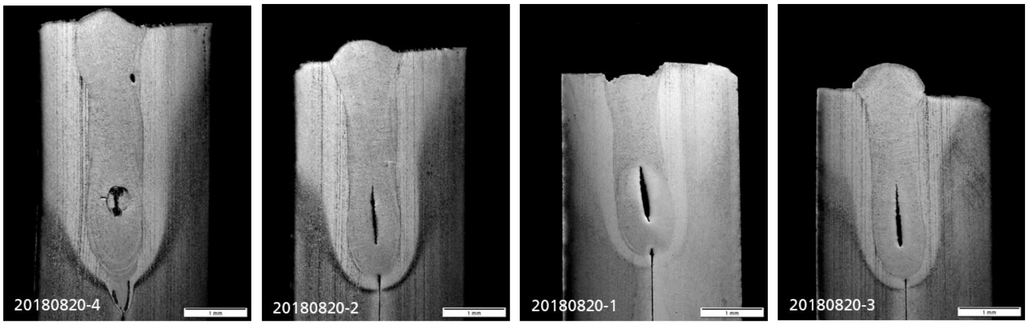
Fig. 1. Modified KS2 specimens for testing edge welds

The modified specimen is characterised by a free punch providing access of the laser beam to the joint between the webs (Figure 1b). The free punch was designed in a way to maintain number and position of the bores used for fixing the specimens in the testing machine. A weld with a length of 18 mm effective cross-section was applied. The welding parameters were adjusted to attain a penetration depth of twice the thickness of the thinner sheet. Tests according to the LWF KS-2 procedure have been performed in a quasi-static regime at a speed of deformation of 10 mm/min. Load angles were varied from pure shear at 0° in steps of 30° to 90° for the peel condition perpendicular to the weld seam. Load and displacement have been registered for the assessment.

3. Results

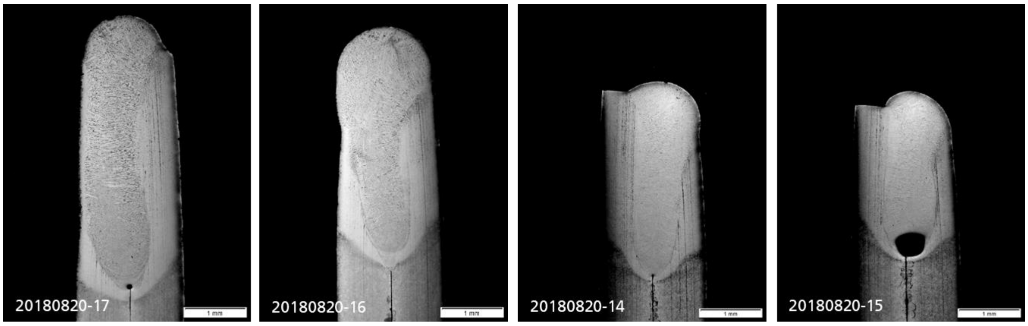
3.1. Pre-study

To estimate the basic parameters, a preliminary investigation was done at the Fraunhofer ILT on similar material joints. Figure 2 shows photographic representations of macro-sections produced with a beam power of 4 kW and a focus diameter of df = 600 µm on sheets of different thickness. The welding speed was varied between 3 and 6 m/min. The welding depth shows a clear influence of the welding speed, while it is independent of the sheet thickness. In the welds shown in the upper row of images (drawing file (a)), hot cracks are visible in the lower third of the weld. These can be attributed to the fixed clamping of the workpiece and the high stiffness of the thicker sheets.



v_s = 3 m/min	v_s = 4 m/min	v_s = 5 m/min	v_s = 6 m/min
t_s = 4,3 mm	t_s = 3,8 mm	t_s = 3,1 mm	t_s = 3 mm

a) edge welds in 1.4034 PH, sheet thickness d = 1,5 mm



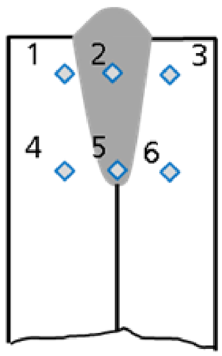
v_s = 3 m/min	v_s = 4 m/min	v_s = 5 m/min	v_s = 6 m/min
t_s = 4 mm	t_s = 3,9 mm	t_s = 3,3 mm	t_s = 2,4 mm

b) edge welds in 1.4034 PH, sheet thickness d = 0,9 mm

Fig. 2. Photographic representation of macro-sections of edge welds

Under the selected clamping conditions, the requirement that the welding depth is equal to double the plate thickness cannot be reliably achieved. This can be improved by adapted beam shaping or beam manipulation. For example, a larger focus radius may require a greater energy per unit length. This results in a flatter cooling curve and thus makes it possible to control crack formation. The bottom row of images shows the transverse sections of a joint between two sheets with a thickness of 0.9 mm. The welds are crack-free and show only low porosity.

The hardness behavior and a preliminary estimation of the mechanical properties were performed using a hardness test. The hardness test was performed on non-heat-treated specimens. Figure 3a shows the measurement scheme and results. The measurements were performed on six points, two of which (2 and 5) are located in the weld and four (1, 3, 4, 6) in the heat affected zone. One of the purposes of this was to check whether a self-starting effect occurs. The table of results shows the sample numbers in the columns in the arrangement of Figure 2b and the measured values at the individual positions in the rows. The values measured in the weld are set in red.



a) Measuring scheme

	#4	#2	#1	#3	#17	#16	#14	#15
1	669	623	653	654	663	683	489	666
2	700	703	711	659	676	682	707	657
3	641	686	501	680	693	656	705	710
4	545	525	473	469	602	520	497	617
5	660	703	663	673	703	696	732	703
6	560	507	507	641	612	598	641	686

b) Results of the hardness measurements at a similar weld of 1.4034

Fig. 3. Scheme for hardness measurements and hardness in edge welds at a sheet thickness of 1.5 mm

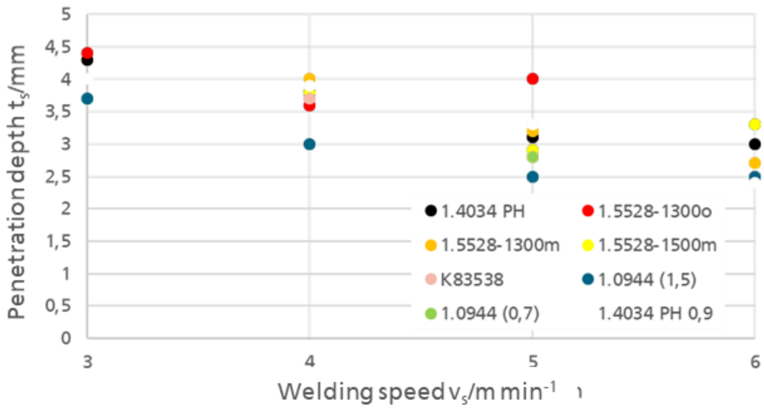


Fig. 4. Penetration depth attained in similar welds in alternative steels

In comparison with the comparable welded I-seams at butt and lap joints, generally higher hardness values were measured. The maximum measurement error after adjustment of the data is ±6HV1The highest values are achieved in the weld with about 690. A comparably high hardness of 659 and 682 HV1 was measured in the upper heat-affected zone. The smallest hardness values were determined in the lower heat-affected zone with 542 and 594; here the values as measured for other impact shapes are reached. One reason for the high hardness is the rapid heat dissipation in the upper region of the weld zone, due to the clamping conditions. In addition, shifts in the alloy composition may be causal for the hardness behavior. A self-tempering effect could not be confirmed. In preparation for welding dissimilar joints, the achievable weld penetration depth as a function of beam power and welding speed was also determined for alternative grades in tests. The results are shown in Figure 4 as a curve of the weld penetration depth as a function of feed rate. As expected, the values obtained lie on a hyperbola. A significant influence of the materials on the welding penetration depth cannot be detected.

3.2. Parameters variation and beam weaving

To be able to evaluate the welds, certain criteria were defined which allowed a distinction to be made between ok and not ok. For example, the weld penetration depth t_s should be ≥ 2·tmin where t_{min} corresponds to the thinner plate thickness in the joint. According to DIN EN ISO 13919-1, cracks are not allowed, so no cracks must not be visible in the macro-sections. The weld should be positioned centrically to the joint gap. A trapezoidal shape with the lowest possible inclination of the flanks was aimed for as the cross-sectional shape. In the investigation of the 1.4034 in similar material combination, parameters were found to fulfill the requirements both with and without oscillation. Figure 5 shows an overview of the test parameters. Parameters that lead to defect-free seams are marked with black dots, those that lead to cracked seams with red dots.

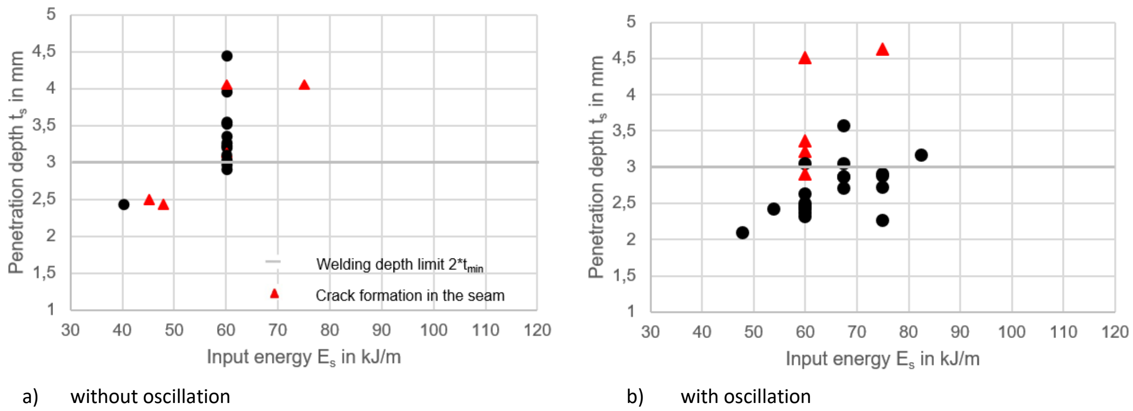
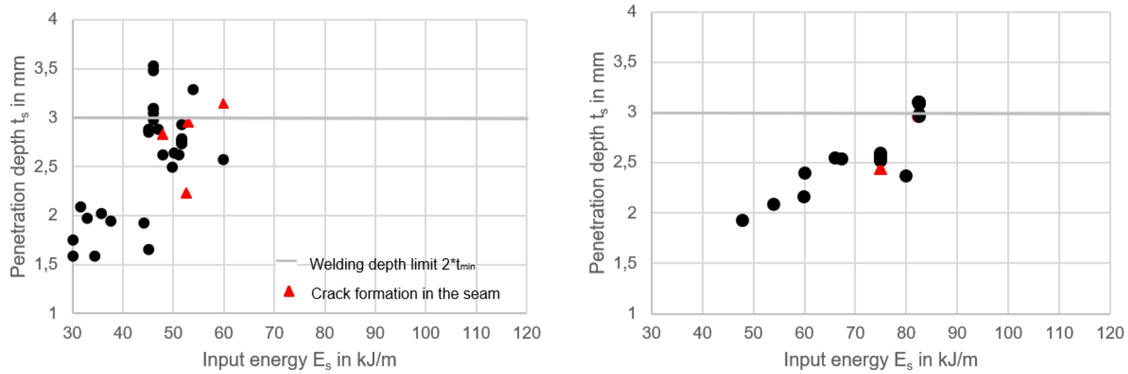


Fig. 5. Penetration depth in similar welds in 1.4034 dependent on the input energy

Both variations had defects. The most common defects were longitudinal cracks (perpendicular to the gap) and cracks horizontal to the gap. The welds with oscillation increased the width of the weld joint but required increased laser power. The weld surfaces were more unstable with oscillation and spatter formed during the process. An advantage of oscillation over the welds with the static laser beam was not evident for the material combination. (Figure 5a). The values for weld penetration depth, weld width and seam shape fulfill the requirements. Compared to the previous samples (1.4034/1.4034), the power must be reduced for this combination, since greater weld penetration depths could already be achieved at lower laser power or higher welding velocity. Oscillation widened the seam, but this combination also produced spattering, which, in contrast to welding with the static laser beam, led to seam penetration. (Figure 5b).

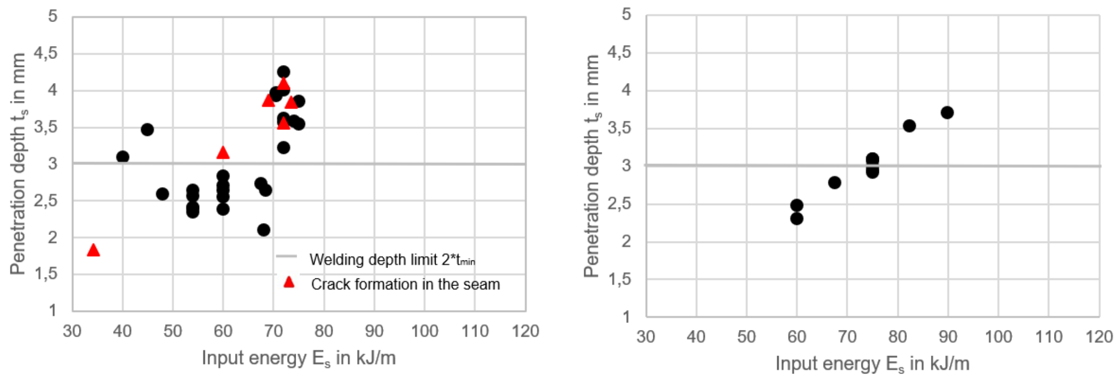
The material combination 1.4034/1.0944 fulfills the requirements. To achieve the welding depth of 3 mm without oscillation, less energy is necessary compared to the 1.4034 similar combination. The energy input for the specimens with oscillation must be almost doubled compared to the welds without oscillation (Figure 6 a and b). The material combination yields a low number of defects in the form of cracks. If a wider connection to both joining partners is not necessary, no advantage of beam oscillation compared to the static laser beam can be seen with this combination.



a) without oscillation

b) with oscillation

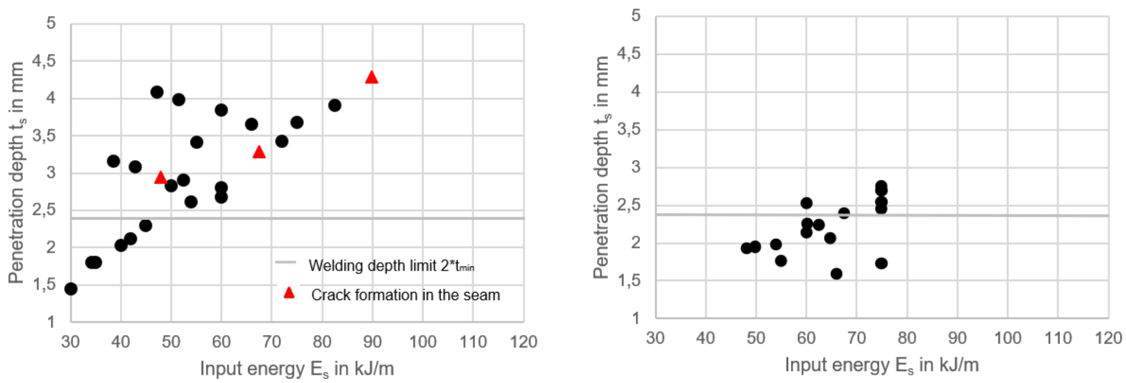
Fig. 6. Penetration depth in the combination 1.4034/1.0944 dependent on the input energy



a) without oscillation

b) with oscillation

Fig. 7. Penetration depth in the combination 1.4034/1.5528 dependent on the input energy

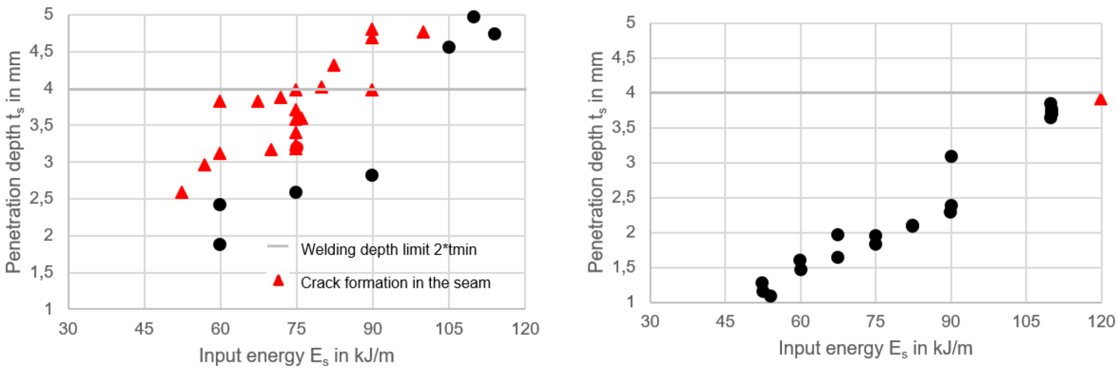


a) without oscillation b) with oscillation

Fig. 8. Penetration depth in the combination 1.4034/1.4678 dependent on the input energy

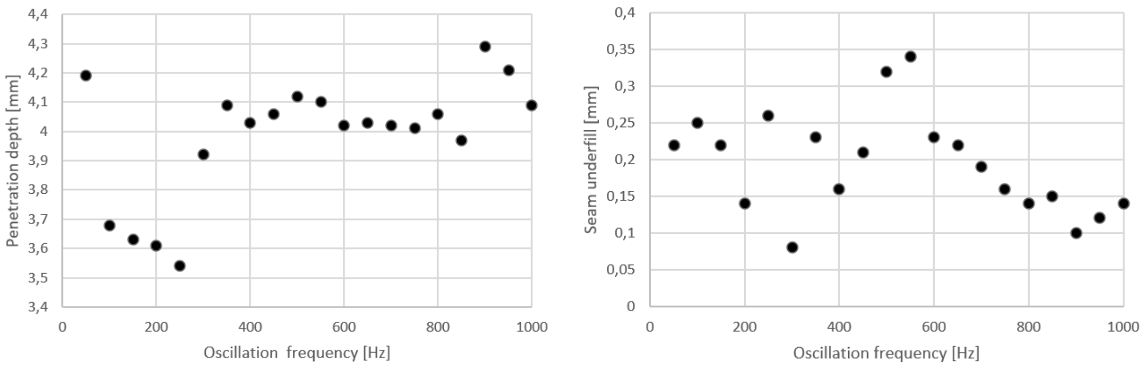
The material combination 1.4034/1.5528 (Figure 7) could be welded both with and without oscillation. No noticeable number of defects were produced. Defects could be observed at high speeds or due to an increased weld penetration depth of > 3.15 mm. The shape of the weld with oscillation is clearly different from the weld produced with a standing beam. The oscillating weld is wider and equally bonded in both materials. The seam from the standing beam is narrower and more tapered.

The combination 1.4034/1.4678 showed only few cracks in the trials (Figure 8). With oscillation, increased spatter formation and the associated large seam incidence and clearly visible distortion of the weld specimens could be observed. The requirements could be achieved for a welding speed up to 7 m/min. Overall, the welds are also feasible without oscillation if the increased bond width can be dispensed with.



a) without oscillation b) with oscillation

Fig. 9. Penetration depth in the combination 1.4034/1.0984 dependent on the input energy

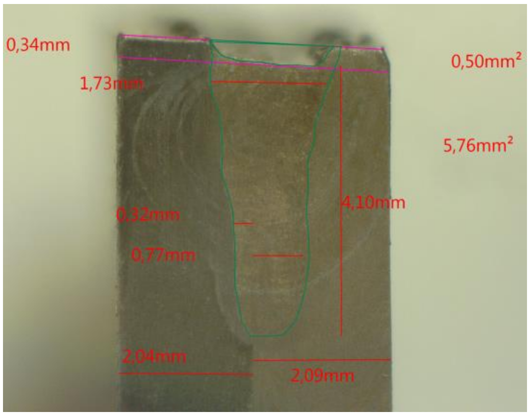


a) Penetration depth b) seam underfill

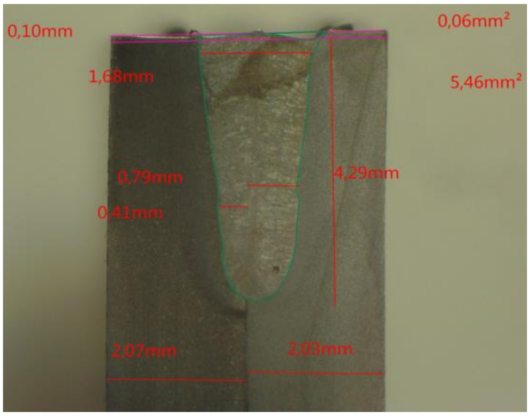
Fig. 10. Effect of oscillation frequency on the seam geometry

In the material combination 1.4034 PH/1.0984, weld defects in the form of cracks formed remarkably often in the welds without beam oscillation. Oscillation significantly reduced the crack rate, as can be seen in the comparison of Figure 9 a and b. However, the oscillation resulted in strong spatter formation, and thus a large seam underfill. The required welding depth of 4 mm was not achieved even with a comparatively high line energy.

The investigation with beam oscillation was carried out on the material pairing 1.4034/1.0984, as the critical combination, with constant parameters. Both materials had a sheet thickness of 2 mm. The tests were performed from 0 Hz to 1000 Hz with an increase in steps of 50 Hz increments. The amplitude of the was fixed at 0.5 mm in y direction (orthogonal to the welding direction). In addition to the preparation of macro-sections and tabular as well as photographic documentation, photographic recordings of the weld surface and video recordings of the weld were made by high-speed camera. This provided insight into the behavior of the melt and the nature of spatter formation. For example, a maximum of melt ejections was found at an oscillation frequency of 500 to 600 Hz. A resonant coupling of the oscillation to the natural frequencies of the welding capillaries is suspected as the reason. The spatter formation is accompanied by a measurable incidence of the upper weld seam (seam incidence). In the measurement, the weld penetration depth criterion was supplemented by the amount of seam incidence and included in the evaluation of the tests Figure 10 shows the seam depth (a) and seam underfill (b) as a function of the oscillation frequency. It was found that at a frequency of 900 Hz, a maximum weld penetration depth is achieved with the lowest spatter formation and the smallest seam underfill.



a) 550Hz oscillation frequency



b) 900Hz oscillation frequency

Fig. 11. Comparison of oscillation frequencies in the cross-sectional view

3.3. Hardness and weld microstructure

Figure 12 show macro-sections of welds after parameter optimization and the corresponding hardness values. The left column shows the macro-sections of joints welded with a static beam, the middle one shows macro-sections of joints welded by a weaved beam. The right column contains representative hardness values.

All welds have a slender shape with largely parallel flanks. In the heat-affected zone and the base metal, the high hardness already measured for the lap joints are measured. From the hardness distribution, it can be concluded that even with thin sheets of 0.9 mm, a tempering effect does not occur in the base material. In the combination with the dual-phase steel, a hardness of 224 HV1 was measured in one measuring point. This hardness corresponds to the tempering hardness that occurs in the heat-affected zone between the coarse grain zone and the unaffected base material. In the weld between the 1.4034 and the 1.4678, a comparatively low hardness was measured with values between 309 and 340 HV1. These low values indicate the presence of a dominantly austenitic microstructure and suggest a comparable intermixing of the materials in the edge weld, compared to the overlap weld. The high hardness in the seams joining the unalloyed and low-alloyed grades to the 1.4034 indicates the presence of a bainitic or dominant martensitic microstructure.

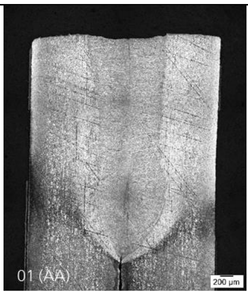
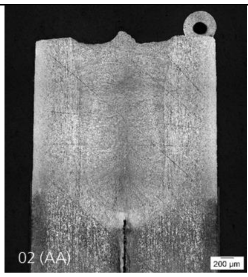
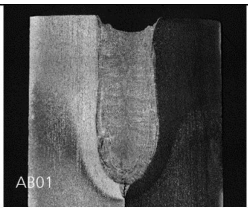
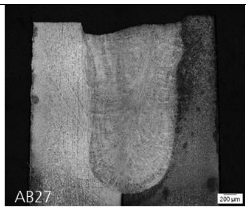
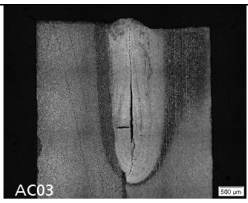
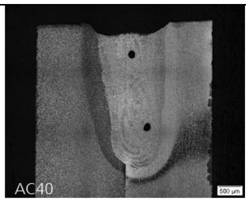
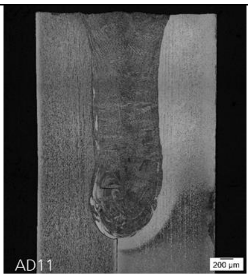
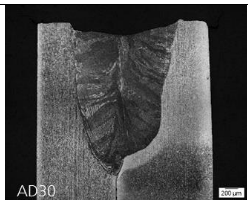
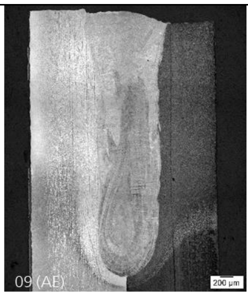
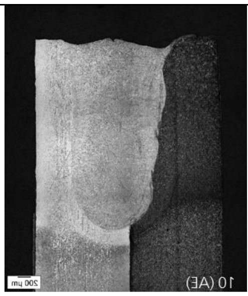
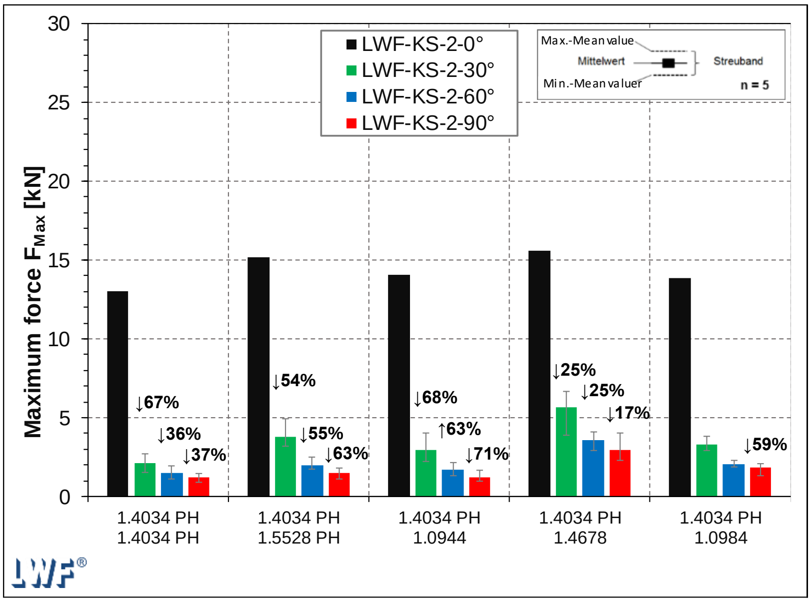
Static laser beam	Oscillated laser beam	Hardness in HV1					
		1	2	3	4	5	6
		694	625	665	529	667	506
		575	677	648	541	633	634
		a) Welding 1.4034 (similar)					
		1	2	3	4	5	6
		650	610	403	531	525	296
		555	534	386	629	569	390
		b) Combination 1.4034/1.0944					
		1	2	3	4	5	6
		228	576	605	223	657	514
		206	629	674	226	641	518
		c) Combination 1.0984/1.4034					
		1	2	3	4	5	6
		284	309	533	428	340	618
		302	320	599	456	340	520
		d) Combination 1.4678/1.4034					
		1	2	3	4	5	6
		644	647	477	502	541	328
		595	669	326	669	669	499
		e) Combination 1.4034/1.5528					

Fig. 12. Macro-sections and hardness in edge welds

3.4. Mechanical properties

The parameters which gave the most stable results were used to produce KS2 specimens. In summary, stable parameters could be determined for all material pairings. Only the behavior of the individual combinations differed, but with the help of oscillation, beam manipulation and varied powers and velocities, the requirements could be met. The clamping condition for the KS2 specimens was realized with the aid of a clamping fixture, which ensures two-dimensional clamping at the same height and thus the same heat dissipation as far as possible. Only the material combination 1.4034/1.0984 was welded with a modified frequency of 1000 Hz due to the investigation of oscillation. Due to the different plate thicknesses from the flat specimens to the KS2 specimens, it was necessary to adjust the laser power. The change in power was again checked using a cross sectional analysis.



Testing method
Quasi-static tensile test
Test speed
10 mm/min (Traverse)
Material 1
1.4034 PH, t = 1,2 mm
Material 2
see abscissa
Joining process
Laser beam welding, tempering
Sesm type
Edge weld
Specimen shape
modified LWF-KS-2

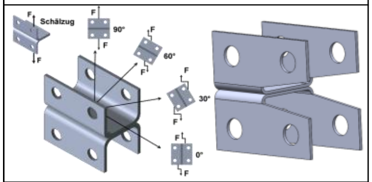


Fig. 9. Comparison of maximum force in quasi-static tensile test

After welding, the specimens were first tempered in the furnace at 400°C for five minutes (holding time). The heating was carried out from room temperature. The smallest loads are obtained with 1.4034 (similar material) with 13 kN being achieved under pure shear load. If the load angle deviates from 0°, the bearable load decreases to approx. 2.5 kN and falls with increasing angle to 1.5 kN at 90°.

Decrease in the load that can be carried: almost all material combinations were found to have a decrease in the maximum load compared to comparable lap-jointed welds, except for the combination with the 1.4678. For this combination, an increase in the ultimate load of one third was measured under shear loading. The decrease in maximum force with increasing tensile head component is also lower.

4. Conclusions

Edge welding is a promising welding process that offers the possibility of reducing the flange length and thus making the lightweight potential of this press-hardened martensitic chromium steel even more usable. The material, which is generally classified as difficult to weld, can be welded without defects in both similar and dissimilar combinations by using the edge welding process. The possibility to reduce crack formations by using high-frequency beam oscillation was demonstrated in this study. The influence of the oscillation frequency on spatter formation was also presented. Comparable to the lap-welded joints of the same material, the tensile tests show a high sensitivity to head tensile loading of the weld. This should be taken up in further studies with the aim to optimize the possibilities of the promising process even further for end applications close to series production.

Acknowledgements

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