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Investigation of the gap bridgeability at high-power laser hybrid welding of plasma-cut thick mild steels with AC magnetic support

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Abstract. One of the challenges of the high-power hybrid laser welding of thick steels is the sensitivity of the process of the process to manufacturing tolerances. This usually leads to a time-consuming preparation of the welding edges, such as milling. The study deals with the influence of the edge quality of milled and plasma-cut steel made of S355J2 with a wall thickness of 20 mm on the laser hybrid welded seam quality. Furthermore, the gap bridgeability and the tolerances towards edge misalignment was investigated. An AC magnet was used as backing support to prevent sagging and positioned under the workpiece, to generate an upwards directed electromagnetic pressure. The profiles of the edges and the gap on the top and root side were measured using a digital camera. Single-pass laser hybrid welds of plasma-cut edges could be welded using a laser beam power of just 13.7 kW. A gap bridgeability up to 2 mm and misalignment of edges up to 2 mm could be achieved successful. Additionally, the independence of the cutting side and the welding side was shown, so that samples were welded to the opposite side to their cutting. For evaluation of internal defects or irregularities, X-ray images were carried out. Charpy impact strength tests were performed to determine the toughness of the welds.

1. Introduction

The hybrid laser arc welding process is a coupling of laser beam welding and arc welding process in a common interaction zone and was developed in the 1970s [1]. The aim of this coupling is to exploit the synergy effects of both welding processes and overcome problems that often occur in pure laser beam welding or arc welding. The high power density of the laser beam creates a narrow keyhole, which enables a deep penetration effect at high welding speeds and low distortion of the welded metal. The additional material, which is fed to the process in the form of molten filler wire enables a better bridgeability against gap and other manufacturing tolerances [2]. Furthermore, the mechanical-



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technological properties of the welded samples can be positively influenced by using of an aimed filler metal and the additional energy of the arc in general, which reduces the cooling rate.

Nevertheless, the beam-based welding processes such as HLAW or LBW are sensitive to gaps and misalignment between the joining parts. Additionally, the edge quality has a major impact on the weld seam quality. Preferably, the edges have to be milled before welding and the joining parts have to be positioned exact to each other and to the laser beam by using expensive clamping technologies. These are time and cost-consuming and can reduce the effectiveness. Studies dealing with the maximum gap bridgeability at hybrid laser-arc welding of thick-walled steels showed, that a gap up to 0.7 mm could be bridged with a transversal oscillating of the laser beam to the welding direction, successfully [3]. The tests were performed at 16 mm thick steels using a solid-state laser. With a carbon-dioxide laser the max. bridged gap at a single-pass was 0.8 mm for welding of structural steel with a wall thickness of 15 mm [4]. Wahba et al. [5] demonstrated the use of cut-wire particles which were filled into an air gap of 2.5 mm before welding. With this technique a homogenous distribution of the elements and a gap bridgeability of 2.5 mm for single-pass welding of 25 mm thick steels could be reached. A ceramic and flux backing support to prevent the drop-outs was necessary. Alternatively, the use of an electromagnetic weld pool support at LBW and HLAW was demonstrated by Avilov et al. [6] and Üstündag et al. [7]. With the contactless backing support, a gap bridgeability up to 1 mm and a misalignment of the edges up to 2 mm at single-pass HLAW of 25 mm thick structural steels could be realized [8]. As it can be seen, the gap bridgeability at beam-based welding processes especially for welding of thick-walled steels in a single-pass presents a major challenge.

Another challenge is the preparation of the edges. The influence of the edge quality and morphology on the seam quality has already been confirmed. At LBW of 20 mm thick-walled steels, a deeper penetration and a better weld quality could be observed when the roughness level of the edges R_a was approx. $6.3 \mu\text{m}$ and the gap between the joining parts was 0.1 mm to 0.2 mm. A further increase of the roughness higher than $R_a 8 \mu\text{m}$ leads to an unacceptable quality of the seams [9]. Farrokhi et al. [10] studied the influence of the edge morphology on the seam quality for milled, abrasive waterjet-cut, plasma-cut and laser-cut steels for double-sided laser hybrid welded 25 mm thick steels. The waterjet-cut and milled enabled a high stability of the welding process and were appropriate for butt joint configuration due to the uniformity and high quality of the edges. For the plasma cut samples, the filler material was increased up to 60 % to fill the resulting typical V-shape groove at plasma cutting. Laser cut samples were welded with approx. 20 % less laser power, due to the striations formed by the cutting process which caused a locally increase of the air gap between the joining parts [10]. Bunaziv et al. [11] reported that the process window for a stable welding process at machined samples was wider during HLAW of 12 mm to 15 mm thick structural steels compared to plasma-cut edges in regard to the root humping effect. Engström et al. [12] stated that laser cut steels up to a wall thickness of 10 mm were welded by HLAW with an acceptable weld quality even with the oxides from the cutting process. For higher wall thicknesses of about 12 mm the oxides should be removed to obtain an acceptable weld quality without pores and excessive and irregular weld penetration.

The aim of this study is to investigate the effect of the edge quality on the weld seam quality for single-pass HLAW of 20 mm thick structural steel S355J2. Thereby, the seam quality and the Charpy impact toughness of the seam on milled and plasma-cut steels are compared.

2. Experimental Setup

All welding experiments were carried out in flat (1G) position using a 20-kW-Yb fibre laser YLR-20000 with a wavelength of 1064 nm and a beam parameter product of 11 mm x mrad. The focal length of the optics was 350 mm. An optical fibre of 200 μm was used for transmission of the laser beam. The focus diameter was 0.56 mm. The welding machine Qineo Pulse 600A functioned as arc welding power source. For the experiments the welding machine was operated in pulse mode with a pulse frequency of 180 Hz. All hybrid laser arc welds were executed with an arc leading orientation and a torch angle of 25° relating to the laser beam, which was perpendicular to the workpiece. The distance between the two heat sources was 4 mm. The focal position of the laser beam was set to -6 mm.

The experiments were carried out with the electromagnetic weld pool support technique. Therefore, an AC magnet was positioned 2 mm below the workpiece and operated with an oscillating frequency of 1.2 kHz and a magnetic flux density of 80 mT to 100 mT. The magnetic field was produced between two magnet poles and was directed perpendicular to the welding direction, while the induced eddy currents were parallel to it. The formed Lorentz forces and resulting electromagnetic pressure were directed upwards to counteract the hydrostatic pressure and to prevent the sagging. The magnet and the optical head of the laser and GMAW torch were in a fixed position, while the welding motion was realized by a movement of the external axis. The experimental setup is shown in Figure 1.

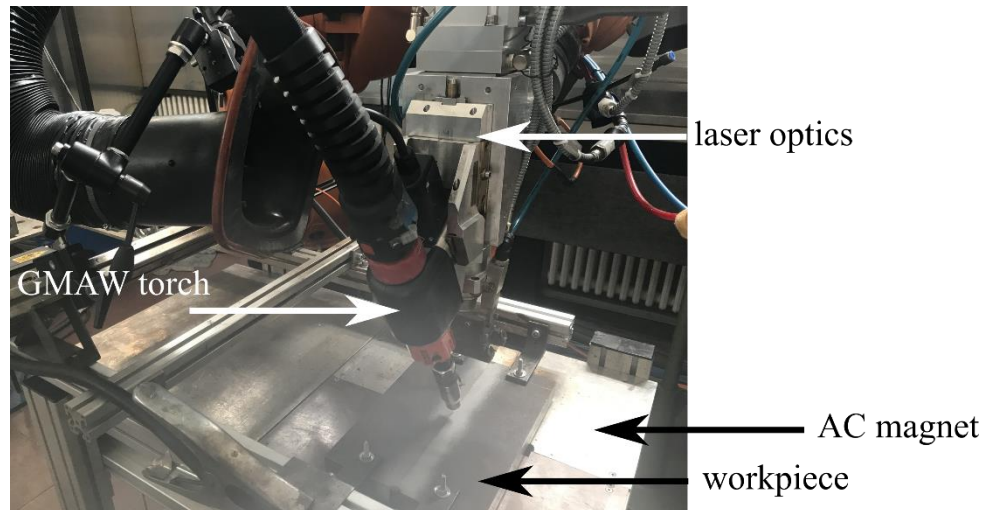


Figure 1. Experimental set-up of hybrid laser-arc welds with electromagnetic weld pool support

For this study, S355J2 steel grade with a plate thickness of 20 mm was used in butt-joint configuration with a square groove. G3Ni1 (solid wire) according to EN ISO 14341 with a wire diameter of 1.2 mm was used as filler wire. The shielding gas was a mixture of argon with 18 % CO₂ with a flow rate of 20 l min⁻¹. The chemical composition of the used material and filler wire are shown in table 1.

Table 1. Chemical composition of base material and filler wire, shown in wt%

Material/Element	C	Mn	Si	P	S	Cr	Ni	Mo	Al	Cu	Fe
S355J2	0.08	1.3	0.29	0.019	0.004					0.08	bal.
G3Ni1	0.08	1.4	0.612	0.004		0.014	0.73	0.08			bal.

Before welding, the edge profile of the plasma-cut sample was measured by a laser profile scanner scanCONTROL with a line linearity of 3 μm and a measuring speed up to 10 kHz and a laser wavelength of 405 nm. The travel speed during the measurements was 1.5 m min⁻¹. Figure 2 shows the edge profile of the plasma-cut sample. It can be noted that the profile is similar to a V-groove shape with a gap of up to 3 mm on the surface. After a tack weld on the front edges, the gap on the top surface and bottom for the plasma-cut sample were measured by digital camera. The records were evaluated by an edge detection tool. Figure 3 shows the measured gap of the plasma-cut sample over the entire seam length.

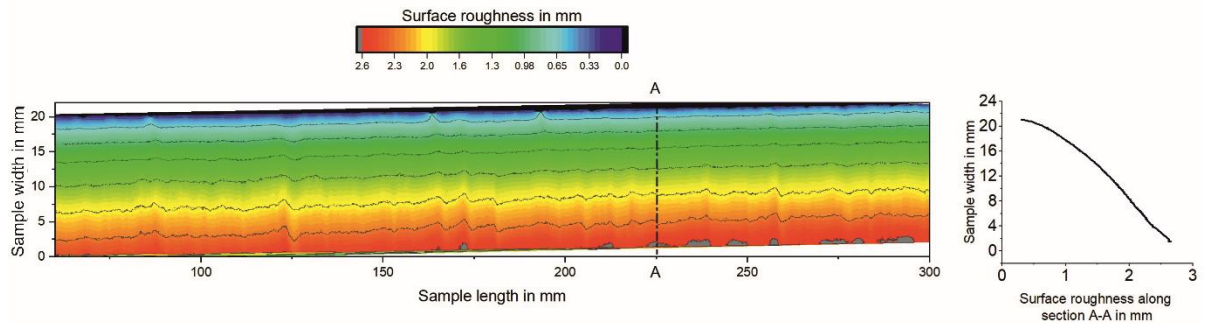


Figure 2. Edge profile of plasma-cut 20 mm thick S355J2 plate; profile measured by a laser-profile scanner

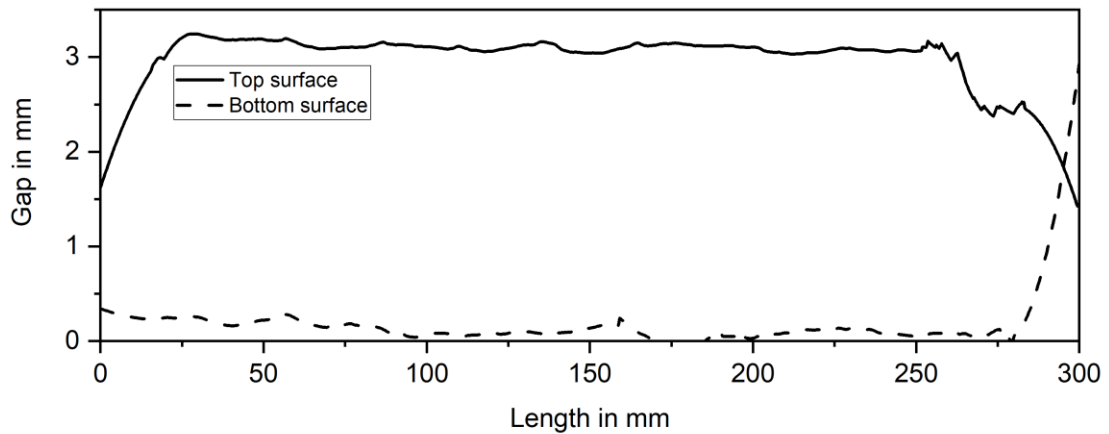


Figure 3. Gap sizes for the plasma-cut sample on the top surface and bottom surface after tacking on the front edges

SEM images of the plasma-cut samples show a formation of an oxide layer on the surface due to the add of oxygen to the cutting gas. The SEM images are shown in Figure 4. Therefore, some plasma-cut samples were sand-blasted before welding. With the sandblasting the oxide layer could be removed.

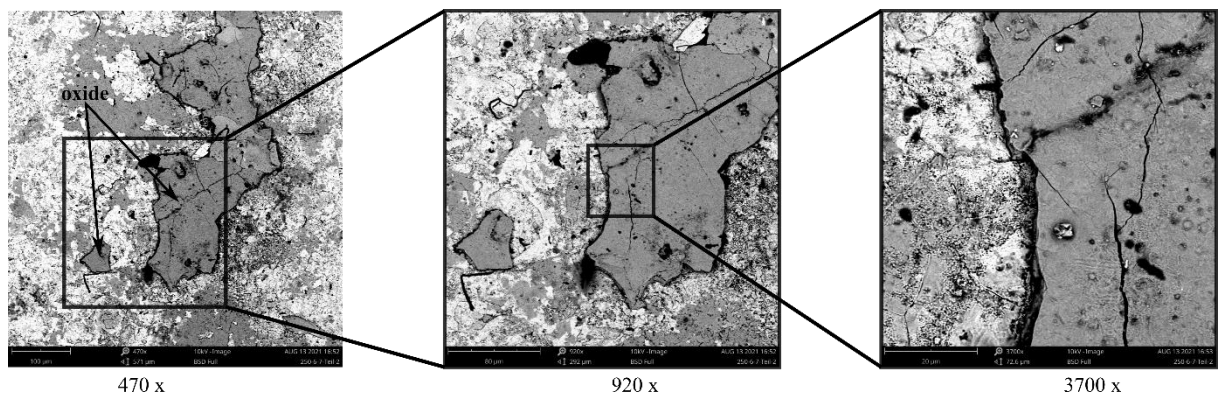


Figure 4. SEM images of plasma-cut samples with an oxide layer

For the inspection of the external and internal defects visual tests and X-ray tests were carried out, respectively. At some selected samples cross-section were taken. Additionally, Charpy V-notch impact test specimens were extracted in the middle of the material thickness to test the impact toughness of the seam. The V-notch was set in the fusion zone.

3. Results

Single-pass laser hybrid welds of 20 mm thick S355J2 could be realized for the all tested samples: milled, plasma-cut and plasma-cut and sand-blasted. For the milled sample, a stable full-penetrated weld was carried out with a laser beam power of 17 kW at a welding speed of 1 m min⁻¹. The wire feed speed was 12 m min⁻¹ (38.6 V and 294 A). The visual inspection did not reveal imperfections such as incomplete penetration, sagging or undercuts. For the plasma-cut samples, the welding speed had to be reduced to get a wider seam to ensure a seam without sidewall lack of fusion. The welding speed was set to 0.75 m min⁻¹. The laser beam power was reduced to 13.7 kW. In all samples, the root of the seam was ideally compensated by the electromagnetic weld pool support system, why the seams satisfied the requirements related to the quality level B according to ISO 12932. The oscillating frequency and the magnetic flux density remain unchanged. The outer appearances of the seams are shown in Figure 5.

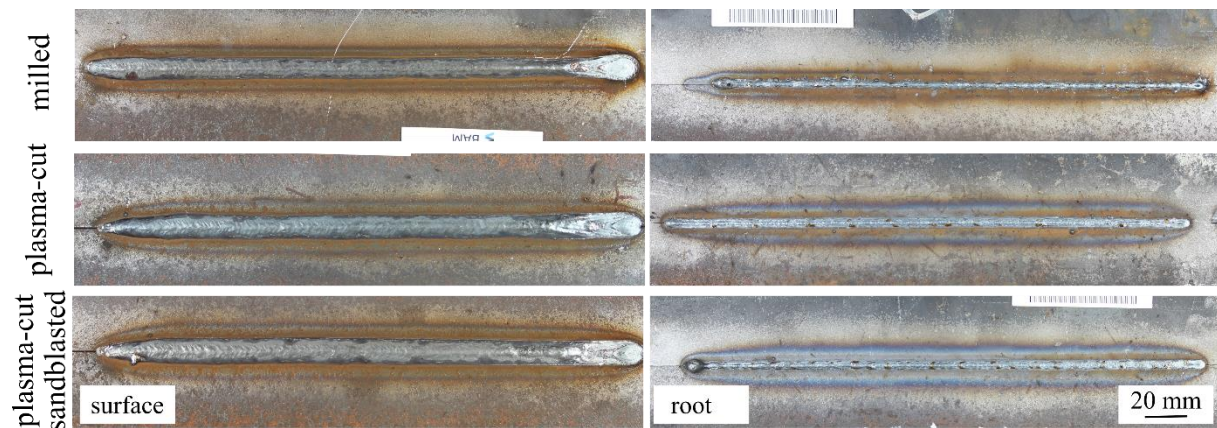


Figure 5. Outer appearance of the laser hybrid welds with electromagnetic weld pool support on milled, plasma-cut and plasma-cut with sandblasted edges

The X-ray images show that the seams are free of defects such as cracks, pores or sidewall lack of fusions apart in the start area and end crater. Figure 6 shows the X-ray images of the seams.

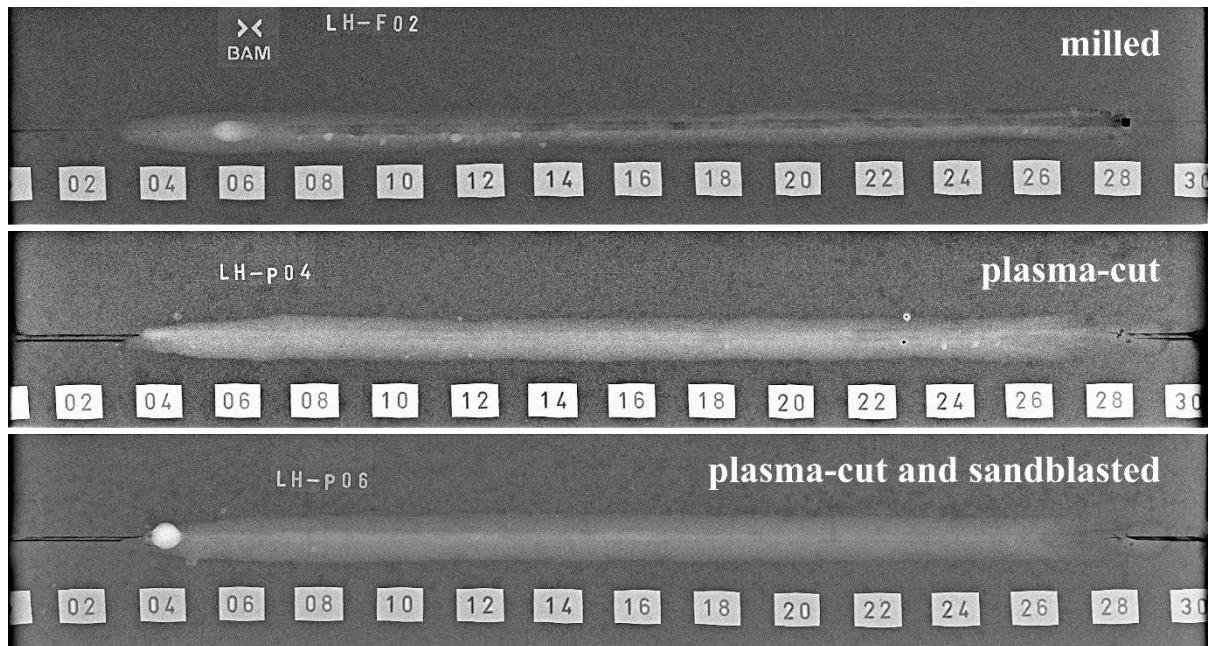


Figure 6. X-ray images of the laser hybrid welds with electromagnetic weld pool support on milled, plasma-cut and plasma-cut with sandblasted edges

The weld shape formations correspond to a typical wine-cup shape and can be divided into two zones: an arc-zone with a wide seam and heat affected zone in the upper part and a laser zone with a narrow and nearly parallel seam flanks in the root part, as shown in Figure 7.

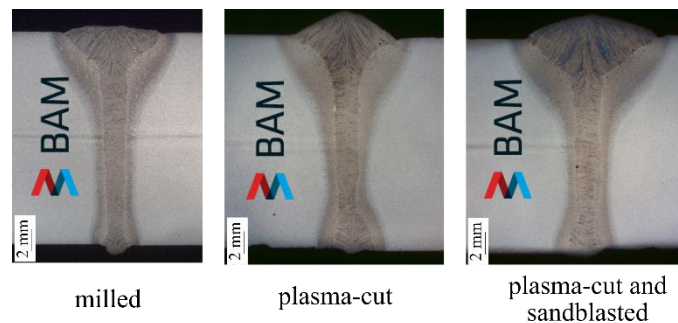


Figure 7. Cross-sections of the laser hybrid welds with electromagnetic weld pool support on milled, plasma-cut and plasma-cut with sandblasted edges

Additionally, the gap bridgeability and misalignment of edges for plasma-cut steels were investigated. A pre-set gap up to 2 mm could be bridged during single-pass laser hybrid welding. Therefore, the welding speed and the laser beam power were decreased to 0.5 m min^{-1} and 12 kW. In contrast, the wire feed speed had to be increased up to 15 m min^{-1} due to the higher volume, which had to be filled. The misalignment of the edges up to 2 mm could be welded in a single-pass using 13.7 kW laser beam power at a welding speed of 0.75 m min^{-1} and with a wire feed speed of 12 m min^{-1} . The magnet parameters remain unchanged. Figure 8 shows the cross-sections for the maximum gap bridgeability and misalignment of edges achieved in this study with a high quality of the seams. δ_0 is the natural gap which has appeared after the cutting process.

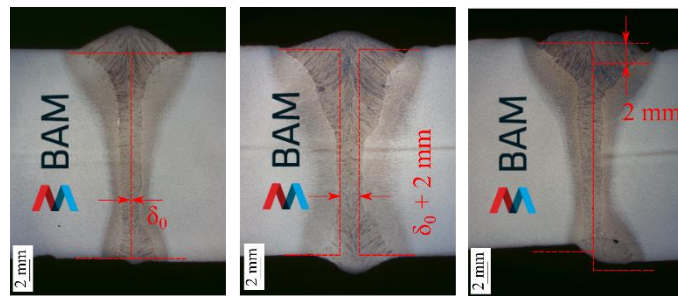


Figure 8. Cross-sections of the laser hybrid welds with electromagnetic weld pool support on plasma-cut samples with different gap and misalignment of the edges

Afterwards, the Charpy impact toughness of the seams were tested. All the tests were conducted in accordance with EN ISO 148-1 at a testing temperature of $-20\text{ }^{\circ}\text{C}$. Five samples each were tested. The results of the Charpy impact tests are summarized in Table 2. For the milled samples the mean absorbed energy was $54\text{ J} \pm 16\text{ J}$. For the plasma-cut samples with and without sandblasting, the mean absorbed energy were $57\text{ J} \pm 17\text{ J}$ and $54\text{ J} \pm 12\text{ J}$, respectively. The minimum required impact energy of 27 J at a testing temperature of $-20\text{ }^{\circ}\text{C}$ were achieved for all the tested samples. The evaluation of the fracture surface morphology revealed a ductile fracture for the samples. Exemplarily, SEM images of the fracture surface of a tested sample is shown in Figure 9.

Table 2. Results of the Charpy impact tests at a testing temperature of $-20\text{ }^{\circ}\text{C}$

Sample	Mean absorbed energy KV in J	Standard deviation in J	n
milled	54	16	5
plasma-cut	54	12	
plasma-cut and sandblasted	57	17	

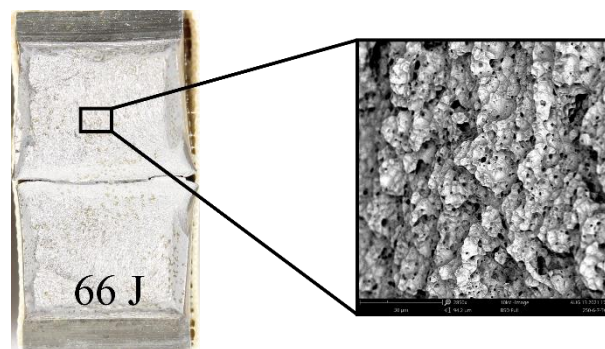


Figure 9. Tested Charpy V-notch impact specimen with an absorbed energy of 66 J and related SEM image with a ductile fracture morphology

4. Summary

Experimental investigations on single-pass HLAW of 20 mm thick structural steels of grade S355J2 were performed. Therefore, plasma-cut samples with and without sandblasting were compared to milled samples. An electromagnetic weld pool support system, which works contactless was used to prevent the sagging. The experiments show that the sensitivity of the HLAW process to gaps and misalignment of the edges could be reduced so that potential industrial application can be increased. For the plasma-

cut samples the welding speed was decreased to avoid sidewall lack of fusions. The Charpy impact tests show that all the tested samples meet the minimum requirements with regard to the absorbed energy. The oxide layer at the non-sandblasted samples had no influence on the Charpy impact toughness of the weld.

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