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MULTIPLE-WIRE SUBMERGED ARC WELDING OF HIGH-STRENGTH FINE-GRAINED STEELS

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ABSTRACT

Ensuring the required mechanical-technological properties of welds is a critical issue in the application of multi-wire submerged arc welding processes for welding high-strength fine-grained steels. Excessive heat input is one of the main causes for microstructural zones with deteriorated mechanical properties of the welded joint, such as a reduced notched impact strength and a lower structural robustness. A process variant is proposed which reduces the weld volume as well as the heat input by adjusting the welding wire configuration as well as the energetic parameters of the arcs, while retaining the advantages of multi-wire submerged arc welding such as high process stability and production speed.

KEY WORDS: submerged arc welding, high-strength fine-grained steels, mechanical properties of the joints, energy parameters of the arc

INTRODUCTION

Submerged arc welding (SAW) with wire electrodes has a wide range of application in the manufacturing of numerous assemblies and components of various branches, such as large-diameter pipe manufacturing, the oil and gas industry, shipbuilding, the petrochemical industry, hydropower plants and offshore wind energy. Due to the high deposition rate of the process, a continuous production with a high cost-effectiveness can be achieved. For components with a thickness up to 10 mm, the single-wire SAW is sufficient. Parts with a larger thickness, require an increased deposition rate, which can be achieved through the application of multiple wire electrodes [1]. Especially, multi-wire SAW processes with up to five wire electrodes have proven successful [2].

However, the application of such highly efficient SAW process variants on modern high-strength steels (yield strength above 355 MPa) is challenging, because of the excessive heat input due to the large volume of the liquid weld pool [3] and the resulting softening in certain areas of the heat-affected zone (HAZ) [4]. These areas suffer from a decreased toughness as well as decreased strength properties of the welded joint [5, 6]. In particular, this problem concerns high-strength thermo-mechanically treated fine-grained steels, whose high mechanical-technological properties are achieved through the specifically adjusted thermo-mechanical rolling process. The fine-grained microstructure of these steels can be irreversibly destroyed in the HAZ, so that the width of the softening zone is essentially dependent on the welding process used and on the line energy [7, 8]. For comparison, a single-wire SAW process has a typical deposition rate of about 8 kg/h, while a five-wire SAW process can achieve a deposition rate of 90 kg/h [2, 9]. The line energies for both process variants are about 2.5 kJ/mm and 10 kJ/mm, respectively. In DIN EN 10225:2009 [10] a nominal energy per unit length of 3.5±0.2 kJ/mm for SAW of fine-grained structural steels for fixed offshore structures is recommended. However, the maximum allowable line energy may be 5±0.2 kJ/mm if the material requirements are not met at 3.5±0.2 kJ/mm. In the manufacturing of large-diameter pipes for the oil and gas industry, an increase in pipe wall thickness above 21 mm leads to an increase in heat input above 5 kJ/mm during welding, resulting in severe overheating and slow cooling of the metal in the HAZ. The specified heat input for a five-wire SAW process is thus far above the recommended values.

The presented welding process parameters as well as the requirements of the standard indicate a contradiction to the application of the multi-wire SAW process. This contradiction is due to the fact that, on the one hand, multi-wire submerged arc welding is highly interesting for the metalworking industry because of its cost-effectiveness. On the other hand, due to its process-specific properties, the use of this process leads to the fact that the mechanical-technological values of the welded joints are negatively influenced.

The objective of this work is to investigate process limits of a five-wire submerged arc welding process with respect to maximum welding speed, penetration depth and heat input by means of welding tests on thick-walled pipes. Furthermore, the possibilities to reduce the heat input by adjusting the process configuration should be shown.

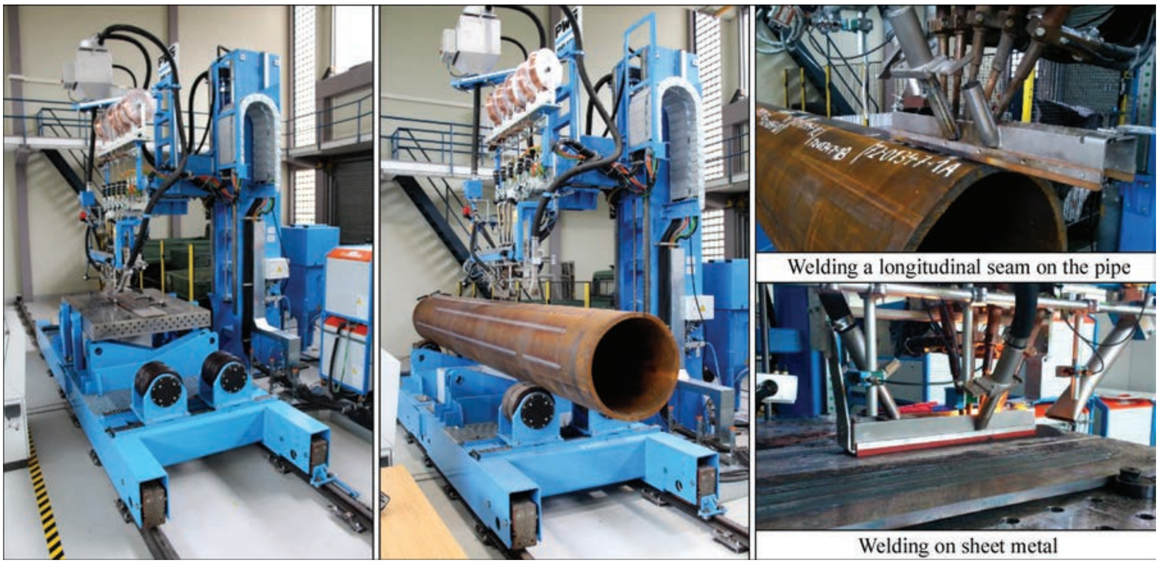

Figure 1. Five-wire SAW test stand for welding sheets and tubes at Fraunhofer IPK in Berlin

WELDING EQUIPMENT AND MATERIALS

The welding experiments were conducted on a full-scale industrial welding system (SMS group GmbH) for longitudinal five-wire SAW on large-diameter pipes. The arcs are supplied with current by five electronically controlled current sources of type PERFECTarc® 1500 AC/DC (SMS group GmbH) with a total current of up to 7500 A. The resulting advantages are not limited to high deposition rates and welding speeds. With a programmable waveform for current and voltage, the welding result can be modeled with respect to various factors (e.g. weld geometry) [11]. Both, flat specimens with a length of two meters and large pipes with a length of up to six meters can be welded on the system. The transport carriage with the component to be welded can be moved at a speed of up to 6 m/min. The five-wire SAW system with two different geometries of specimens is shown in Figure 1.

In the conducted welding tests, pipe sections made of pipeline steel grade X70 according to API 5L or L485MB according to DIN EN 10208-2 (material No.1.8977) were used. The used welding consumables were solid wires BA S2Mo according to EN ISO 14171-A (EN 756) and an agglomerated welding powder of the aluminate-based type BF 5.1.

EXPERIMENTAL PROCEDURE AND RESULTS

Welding tests were performed on six meter long pipe sections with an outside diameter of 914.4 mm (36″) and a wall thickness of 39 mm using the five-wire submerged arc welding method. The pipes used were the longitudinally welded pipe sections, which were provided with a tack weld as well as an inner layer. The welds investigated were therefore made as external welds in a 15 mm deep V-joint with an opening angle of 70°. A welding speed of ≥1 m/min, which was demanding for the given edge preparation, was set as a target. A calculation of the weld volume to be filled showed that a deposition rate of the process of at least 72 kg/hour should be achieved to ensure a closed profile of the weld. In addition, a weld penetration depth of at least 22 mm was targeted in order to melt the existing GMA tack weld and guarantee a secure bond between the outer layer and the previously applied inner layer.

A series of welds was performed with a wire configuration conventional for industrial practice, with the first two torches fitted with the 4.8 mm wires and the third, fourth and fifth wires having a diameter of 4 mm. In the second experiment, a 3.2 mm wire electrode was used on the first torch. The subsequent four wires had a diameter of 4 mm. The weld outer appearance, the metallographic

Figure 2. Outer appearance and cross-section of a SAW-weld. Outer layer welded with the following wire configuration: $d_{1,2}$ = 4.8 mm and $d_{3,4,5}$ = 4 mm: parameters: V = 1.1 m/min, I_1 = 1480 A, U_1 = 34 V; I_2 = 1200 A, U_2 = 38 V; I_3 = 760 A, U_3 = 38 V; I_4 = 650 A, U_4 = = 38 V; I_5 = 650 A, U_5 = 38 V

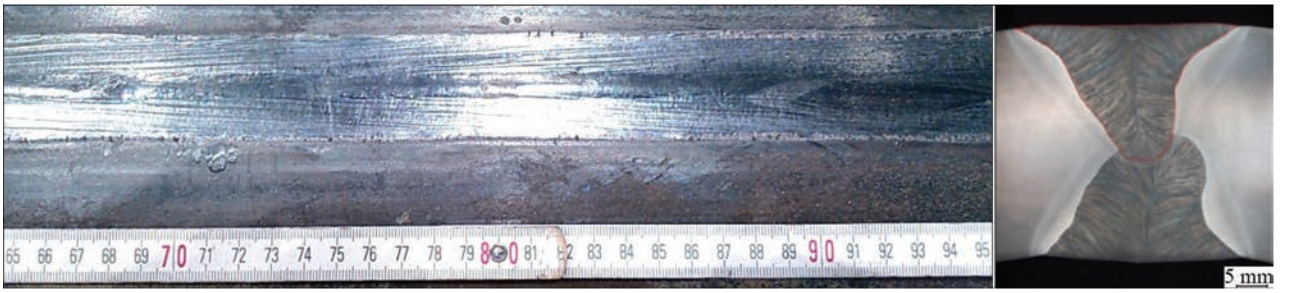

Figure 3. Outer appearance and cross-section of a SAW weld. Outer layer welded with the following wire configuration: d_1 = 3.2 mm and $d_{2,3,4,5}$ = 4 mm: parameters: V = 1.2 m/min, I_1 = 1200 A, U_1 = 32 V; I_2 = 1150 A, U_2 = 36 V; I_3 = 780 A, U_3 = 42 V; I_4 = 760 A, U_4 = = 44 V; I_5 = 760 A, U_5 = 44 V

cross sections and the welding parameters for both process variants are shown in Figures 2 and 3.

The control system of the welding current sources made it possible to record all relevant process data such as welding current, voltage and the welding and wire feed speed during welding at a sampling rate of 50 Hz and to use them for further analysis of the welding process. The recorded data of the welding process are shown as an example in Figure 4.

The smooth progressions of the welding current and voltage signals for all five wires indicate that the welding process is stable. The actual deposition rate of the welding processes could be determined from the recorded wire feed rates.

The evaluation of the results showed that the welding process in the configuration presented in Figure 2 could be run at a welding speed of 1.1 m/min. A line energy of 9.5 kJ/mm had to be brought out to achieve a deposition rate of 83 kg/hour. The V-joint was thus completely filled. The seams showed a slight concavity of the top bead of 0.7 mm. With a welding depth of 20.5 mm, a through-welded seam could be produced, so that the seam cross-section was completely closed. However, the welding depth achieved must be considered as borderline, as the inner layer could only just be reached. The process variant with a 3.2 mm leader wire demonstrates a different result (see Figure 3). Here, a greater weld penetration depth of 24.5 mm was achieved than that for the process configuration with the 4.8 mm leading wire. Due to a larger weld penetration depth, the weld exhibited a slimmer profile, resulting in a reduction of the weld cross-section from 425.8 to 379.8 mm^2 (by 10.8 %). The welding speed could be increased up to 1.2 m/min, which produced a flat weld with no concavity. The line energy went down to 9.1 kJ/mm (by 4.2 %).

The temperature cycles during welding were measured with type K thermocouples. Since the weld width was about 40 mm, the thermocouples were placed at a distance of about 20 mm from the center of the V-joint. Hence, it was possible to record the $t_{8/5}$ time in the HAZ, in close proximity to the fusion line. The results of the temperature measurement for the two process variants can be seen in Figure 5. The line energy of the welding process of 9.5 kJ/mm resulted in a $t_{8/5}$ time of 92 seconds. For the process variant with a line energy of 9.1 kJ/mm, the $t_{8/5}$ time went down to 83 seconds. The corresponding cooling rates are 3.2 and 3.6 °C/s. However, if we consider the recommendations on the cooling rate for longitudinal submerged arc welding of

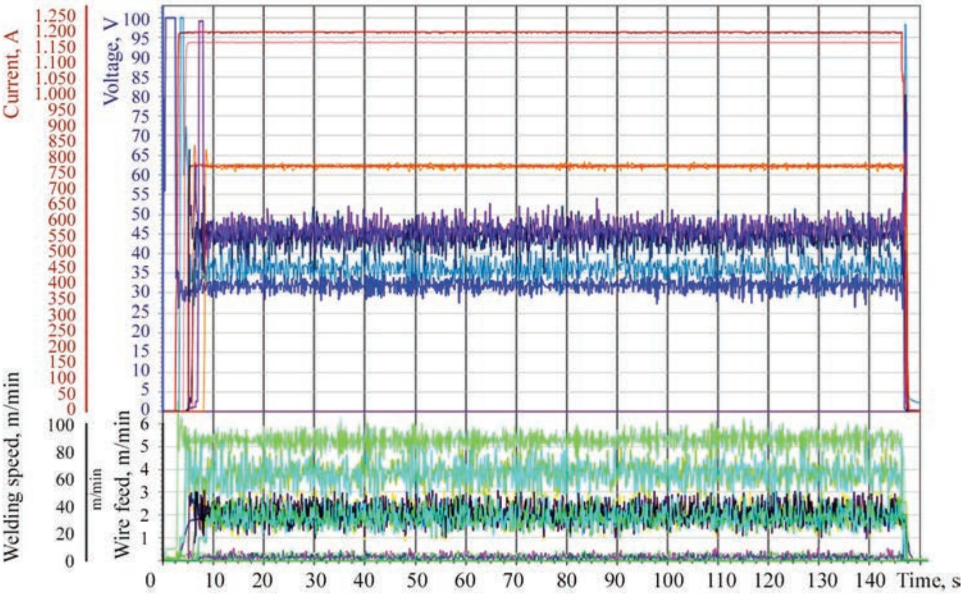

Figure 4. Recorded process data during five-wire SAW welding of a thick-walled pipe

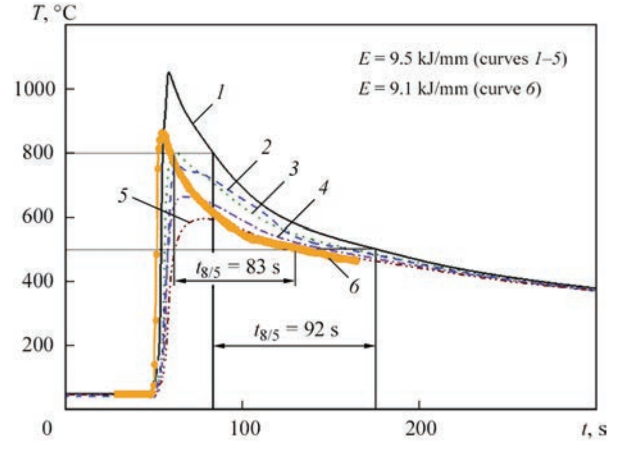

Figure 5. Welding temperature cycles for five-wire SAW welding for E = 9.5 kJ/mm und E = 9.1 kJ/mm, outer seam, tube wall thickness 39 mm

large-diameter pipes, we find that it should be in the range of 10 to 60 °C/s [12–15]. The values considered here are far from the recommended cooling rates. The negative effect of too high line energies on the ductile-plastic properties of HAZ was demonstrated by the hardness tests. Using the *HV*1 hardness test, it was found (Figure 6) that welds produced at 9.5 kJ/mm had a relatively high drop in HAZ hardness (0.79 of the base metal hardness). When welded with 9.1 kJ/mm of line energy, the welds have a lower hardness drop in HAZ (0.91 of the base metal hardness), but this can mean a strength loss of about 10 %.

For both process variants considered, it can be seen that the energy per unit length for five-wire SAW is too high and must be reduced further to avoid the formation of unfavorable microstructures and a reduction in the ductile-plastic properties in the HAZ.

DISCUSSION

In multi-wire SAW, it is common for the first wire to be supplied with DC positive to achieve the maximum weld penetration depth. The subsequent wires are supplied with AC current with a phase shift of 90° in order to minimize mutual magnetic blowout effects.

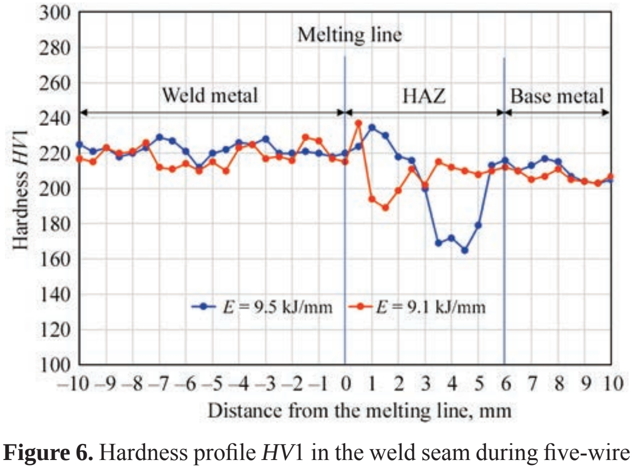

Figure 6. Hardness profile *HV*1 in the weld seam during five-wire SAW welding for E = 9.5 kJ/mm und E = 9.1 kJ/mm, outer seam, tube wall thickness 39 mm

In the process variants considered here, the current of the first 4.8 mm wire was 1480 A and was at the upper power limit of the current source. The current density at the tip of the wire reached 98 A/mm^2, which is a typical value for SAW with a solid wire electrode. In the second process variant, a 3.2 mm wire electrode was used on the first torch. With a significantly higher current density at the tip of the 3.2 mm wire of 125 A/mm^2, it was possible to achieve a weld penetration depth approx. 20 % greater than that for the process configuration with the 4.8 mm wire in front.

Based on this effect, a technological recommendation can be proposed for multi-wire SAW on heat-sensitive fine-grained steels. Basically, to achieve a lower heat input, the edge preparation must be modified accordingly. This means that the opening angle of the joint must be reduced so that the joint is reliably filled at the set welding parameters. The amount of filler metal required to fill the V-joint is thereby reduced and the heat input in multi-wire submerged-arc welding can be lowered. Hence, the line energy does not exceed the specified limit. By reducing the heat input in this way during SAW of thick-walled pipes, cooling rates of up to 10 °C/s and higher can be achieved [15]. For welding an outer layer on a pipe with a wall thickness of 39 mm, this means that the opening angle of the V-joint must be reduced from 70 to 60° and the depth of the V-groove must be reduced by one millimeter from 15 mm to 14 mm. The required deposition rate at a welding speed of 1.2 m/min would be about 67 kJ/h and the line energy 6.5 kJ/mm.

The comparison of the inner seam shape shows that the weld with the thicker leading wire has a semi-circular fusion line, a more favorable shape, than the seam with thinner 3.2 mm wire in front (see Figures 2 and 3). The seam width relates to the seam depth as 1:1 for the seam with 4.8 mm wire in front. For the thinner leading wire, this ratio is at an unfavorable value ≤1 because the seam is too deep. Here, however, it must be noted from macrographs provided that the weld with 3.2 mm wire in front does not have parallel flanks or melt lines, which would indicate unfavorable crystallization font. The weld is rather triangular or fillet-shaped in shape. It can be seen that crystallization occurs perpendicular to the fusion line and crystallines are oriented towards the top region of the weld, i.e. the region of the weld where the lowest mechanical stresses due to heat shrinkage occur. From this point of view, the “width to depth ratio” criterion must be considered critically, especially for the welds where no classical semicircular or almost straight fusion lines can be observed.

Another advantage of the process variant with the thinner leading wire, which should not be underestimated, is that the melted cross-sectional area of the weld seam is approx. 10 % smaller than in the variant with the 4.8 mm wire. This advantage is reflected in the fact that with a smaller weld cross-section, the mixing of the filler metal with the base metal is also lower. It is known from practice that a high degree of mixing is unfavorable for higher-strength grades and must therefore be kept as low as possible.

CONCLUSIONS

Current multi-wire SAW techniques, when welding thick-walled pipes made of high-strength fine-grain steels, are characterized by high energy of the process up to 9.5 kJ/mm and thus do not provide a cooling rate in HAZ within the recommended range of 10–60 °C/s. This limits the applicability of multi-wire submerged arc welding in pipe production, especially when processing higher strength grades X70 and higher according to API 5L.

Based on the welding tests with a five-wire SAW process on a pipe with a wall thickness of 39 mm, it was shown that with decreasing diameter of the leading (DC) welding wire, the penetration depth of the arc and thus also the weld penetration depth increases by approx. 20 % compared to a conventional welding wire configuration. The weld becomes slimmer and has a fillet-shaped weld penetration profile.

Based on this effect, a process recommendation is proposed for minimizing the energy of the line and increasing the cooling rate in the area of the HAZ. Reducing the opening angle of the V-joint in combination with lowering of V-groove depth will result in a reduction of the weld cross-section. The required amount of filler material is reduced and line energy of the process decreases. With this process configuration, it is also possible to switch to a four-wire UP welding process because the use of the fifth wire is no longer necessary due to the reduced deposition rate.

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CONFLICT OF INTEREST

The Authors declare no conflict of interest

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