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A kinematical study of ultrasonic welding based on a system of stationary waves

M. SUSAN[a], L.-G. BUJOREANU[a*], C.L. DUMITRACHE[b], L.C.HANGANU[a], C.BACIU[a]
[a] *Faculty of Materials Science and Engineering, The "Gh.Asachi" Technical University from Iaşi, Bd. D. Mangeron 63, 700050 Iaşi, Romania*
[b] *Faculty of Naval Electromechanics, The Maritime University from Constanţa, Romania*

The paper introduces a model for the formation mechanism of a stable system of stationary waves during submerged arc welding by considering the kinematics of the displacement and vibration of the electrode wire within the oscillating system. Analytical results were in good agreement with experimental results obtained on naval steel sheets. The advantages of ultrasonic welding to classical welding have been emphasized by means of the mechanical characteristics of resistance and plasticity determined from tensile tests.

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1. Introduction

Ultrasonic welding is a complex procedure that enables substantial improvement of mechanical resistance characteristics of thermally influenced zone. The advantages of this procedure, as compared to classic welding, consist in grain refining by fragmenting primary crystals induced by ultrasonics. In the case of submerged arc welding, current practice involves the introduction of ultrasonics into the liquid metal bath by means of an electrode wire which is at resonance. Under these circumstances, of major importance for the welding process is the vibration length of the electrode wire [1].

The present paper aims to develop a model of the formation mechanism of a stable system of stationary waves during submerged arc welding by considering the kinematics of the displacement and vibration of the electrode wire within the oscillating system. In this purpose the following three steps will be done:

(i) determining of the vibration length (l_v) of the electrode wire assuming the formation within the wire of a stable system of stationary waves and considering the kinematics of the welding process;

(ii) performing laboratory experiments on naval steel sheets welded both with and without ultrasonics, in order to test the validity of the developed model;

(iii) analyzing the dependence between mechanical resistance characteristics and relative welding rate, which cumulates the influence of technologic and ultrasonic factors.

2. Calculation of the vibration length of electrode wire

The principle scheme of the submerged arc welding procedure with ultrasonic activation of the electrode wire is illustrated in Fig. 1.

The figure emphasizes the component elements and the wave oscillation at the level of the oscillating system (OS) [2]. The oscillation of the electrode wire is obtained by means of OS which works in conjunction with the ultrasonics generator (USG) [3]. The calculation procedure of OS, its set up and fastening mode to the working frame of the technologic device (which in this case is a welding tractor) by means of a nodal flange have been previously described [4].

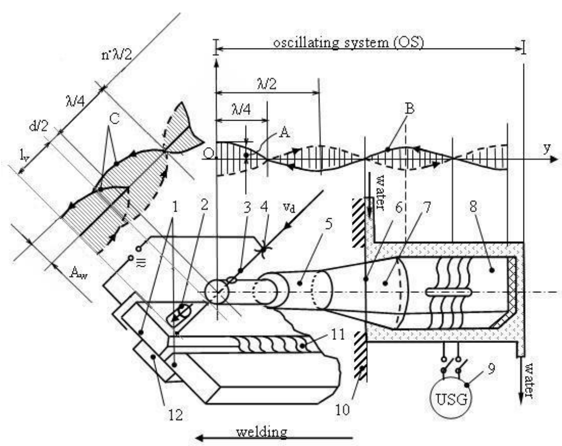

Fig. 1 Principle scheme of the submerged arc welding procedure with ultrasonic activation of the electrode wire: 1 - sheet specimens to be welded; 2 - distribution device of welding flux; 3 - electrode wire; 4 - electrical connections; 5 –cylindrical concentrator in steps from Ti-based alloy; 6 - nodal flange; 7 - conical concentrator; 8 - magnetostrictive transducer; 9 – ultrasonics generator; 10 – resistance frame of the welding tractor; 11 – weld; 12 – support; A - oscillation amplitude; B – waves oscillation along the oscillating system; C – waves oscillation along the electrode wire; λ - wavelength; v_d – displacement rate of the electrode wire; l_v – vibration length of the electrode wire; A_w – maximum amplitude of the electrode wire; ———— progressive wave; – – – – – – regressive wave.

From a technologic point of view, it is important to know the vibration length (l_v) of the electrode wire and the oscillation amplitude (A_w) in the forming zone of the electric arc. These two linear dimensions are determined based on the formation mechanism, in the electrode wire, of a stable system of stationary waves during submerged arc welding. This formation mechanism considers the kinematical elements characteristic for the displacement and vibration of the electrode wire within OS, as illustrated in Fig. 2

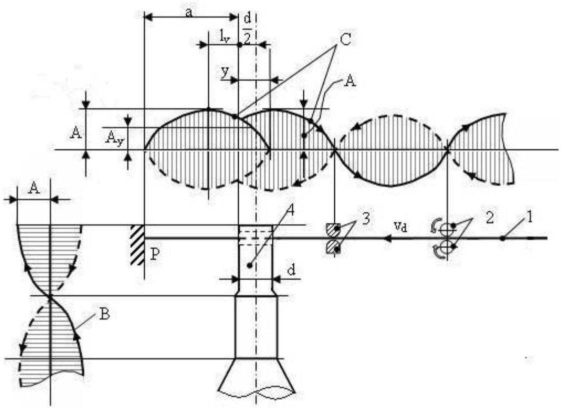

Fig. 2. Scheme of the formation mechanism of a stable system of stationary waves in the electrode wire: 1 – electrode wire; 2 – reflectors of ultrasonic energy (pressure rolls); 3 – electric contacts; 4 - step cylindrical concentrator;
——— progressive wave; – – – – regressive wave.

When passing through the cylindrical concentrator in steps made from Ti-based alloy, the electrode wire's displacement is performed under minimum friction conditions providing $v_v \geq v_d$ [2], where v_v is the vibration rate and v_d is the displacement rate. The kinematical relationship between these two rates and the wave displacement (u) is illustrated in Fig. 3.

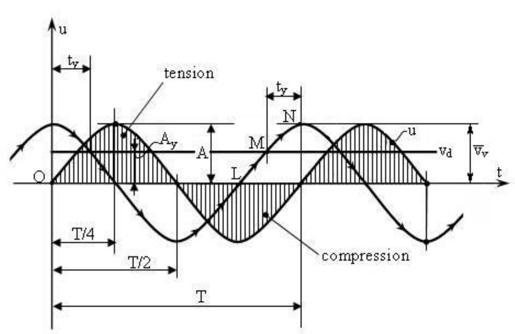

Fig. 3. Kinematical relationship between wave displacement (u), vibration rate (v_v) and displacement rate (v_d) related to a complete oscillation period (T): A – maximum oscillation amplitude; $\overline{v}_v$ - maximum vibration rate

Considering the moment when v_v increases, from point L to point M, it becomes equal to v_d in point M. In this moment, the stress caused by contact friction is released from the cylindrical concentrator to the wire being directed towards its final end in point P (Fig. 2). Assuming the wire as being fixed in point P, at the considered moment a compression wave is induced, during the period of time t_1 [3]:

$$t_1 = 2t_y = \frac{T}{\pi}\arccos\frac{v_d}{v_v} \tag{1}$$

with $\left|\left(\frac{v_d}{v_v}\right)\right| \leq 1$, until v_v becomes lower than v_d and then a tension wave is induced into the wire.

Assuming that the compression wave is reflected by the fixed end of the wire (in point P), it will change its sign and will become tensile starting from point P towards the contact zone with the cylindrical concentrator in steps. Point P can be set at such a distance from the cylindrical concentrator in steps that in the electrode wire a stable system of stationary waves is formed with the maximum amplitude A_w. The displacement amplitude (A_y) in the electrode wire depends on its displacement rate (v_d) and on the OS amplitude (A):

$$2A_y = 2A\sin\omega t_y - v_d t_1 \tag{2}$$

Introducing the values of t_1 and t_y into relationship (2) it follows that:

$$A_y = A\sqrt{1-\left(\frac{v_d}{v_v}\right)^2} - A\left(\frac{v_d}{v_v}\right)\arccos\left(\frac{v_d}{v_v}\right) \tag{3}$$

In order to determine the distance *a* (Fig. 2) from the cylindrical concentrator in steps to point P, where interference occurs between the reflected compression wave and the induced tensile wave, the electrode wire should be considered as a part of the oscillating system [5]. The oscillation frequencies of the compression wave (f_1) and the tensile wave (f_2) are determined as [3]:

$$f_1 = \frac{1}{t_1} \text{ and } \quad f_2 = \frac{1}{t_s - t_1} \tag{4}$$

where t_s is the duration for inducing the compressive or the tensile wave.

Based on the above it follows that the relationship for the maximum amplitude in the welding zone is:

$$A_w = 2A_y\cos\frac{\omega_1-\omega_2}{2}t = 2A_y\cos\frac{\pi t(2t_1-t_s)}{t_1(t_s-t_1)} \tag{5}$$

For large values of the ratio $\frac{v_v}{v_d}$, it follows that $t_s \cong 2t_1$, ω_1

$\cong \omega_2$ and $A_w \cong 2A_y$. For small values of the ratio $\frac{v_v}{v_d}$, it follows that $A_w < 2A_y$.

On the frontal (exit) plane of the cylindrical concentrator in steps the amplitude is A_y while in the welding zone it is A_w. The displacement amplitude A_y corresponds to a distance *y* as shown in Fig. 2. From the condition:

$$A_y = 2A_y \sin\frac{2\pi y}{\lambda} = A_w \sin\frac{2\pi y}{\lambda} \qquad (6)$$

it follows that:

$$y = 0.083\,\lambda \qquad (7)$$

which leads to:

$$a = \frac{\lambda}{2} - y = 0.417\lambda \qquad (8)$$

One can notice from Fig. 2 that the vibration length of the electrode wire (l_v) is half of the distance a, therefore:

$$l_v = \frac{a}{2} = 0.2085\lambda \qquad (9)$$

If the electrode wire would be fixed (v_d = 0) then $l_v = 0.25\lambda$.

The wavelength is determined with [6]:

$$\lambda = \frac{c}{f} \qquad (10)$$

where c is the ultrasonics propagation speed through the wire and f is the resonance frequency of OS. The vibration rate (v_v) is the derivative of displacement (u) in time ($\frac{du}{dt}$). Considering the displacement as $u = A\sin\left(\frac{2\pi}{\lambda}y - \omega t\right)$, if follows for v_v the relationship:

$$v_v = \frac{du}{dt} = \left|\omega A\cos\left(\frac{2\pi}{\lambda}y - \omega t\right)\right| \qquad (11)$$

The maximum amplitude of the vibration rate is obtained for $\cos\left(\frac{2\pi}{\lambda}y - \omega t\right) = 1$, its value being:

$$\bar{v}_v = 2\pi f A \qquad (12)$$

3. Experimental procedure

The scheme of the experimental installation for submerged arc welding with ultrasonic activation of the electrode wire is illustrated in Fig. 4.

Details regarding the functioning mode of the oscillating system (OS) and the ultrasonics generator (USG) were given in a previous work [7]. The length of the cylindrical concentrator in steps is $\lambda/2 = 118\times10^{-3}$ m, λ being determined with (10) considering f = 18 kHz and c = 4260 m/s for titanium based alloy. Inside the step concentrator a copper bushing was pressed for guiding the electrode wire.

The welding tractor, of ELECTRONICA-AST-3 type, was adapted for ultrasonic welding by equipping it with reflectors of ultrasonic energy and nodal flange for OS fastening. The specimens to be welded were made from Romanian naval steel sheets type A, similar to Lloyd's Register notation, with the chemical composition given in Table 1.

The experiments consisted in butt welding of the specimens with dimensions 720 x 300 x $8\cdot10^{-3}$m. Welding was performed both under classical conditions (classical welding-CW) and by ultrasonic activation of the electrode wire, under three variants UW1 ($A = 10\cdot10^{-6}$m); UW2 ($A = 15\times10^{-6}$m) and UW3 ($A = 20\times10^{-6}$ m).

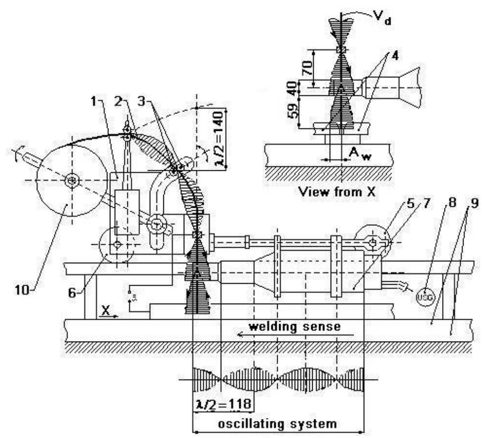

Fig. 4 Scheme of the experimental installation for submerged arc welding: 1 – welding tractor; 2 – electrode wire; 3 – reflectors of ultrasonic energy; 4 - sheet pieces to be welded; 5, 6 – rolls for guidance/displacement of the assembly welding tractor-OS; 7 – magnetostrictive transducer type P.M.S. 15A-18; 8 - ultrasonics generator; 9 – resistance frame; 10 – holder of the electrode wire;
——— progressive wave; – – – – regressive wave..

Table 1 Chemical composition of the Romanian naval steel sheets A (wt. %).

C	Si	Mn	P	S	Cr	Mo	Ni	Al	Cu	W	Fe
0.117	0.041	0.55	<0.002	0.017	0.015	0.013	0.012	0.016	0.015	0.056	Bal.

The welding flux was of FB-10 type and the electrode wire was of S12M12 type with a diameter of 3.25×10^{-3}m. The chemical compositions of the electrode wire, the welding flux and the wire-flux couple resulting after solidification, as determined by means of a SPECTROLAB-ANALYSIS INSTRUMENTS spectrometer, are given in Table 2

The deposition mode of the welding layers is shown in Fig. 5

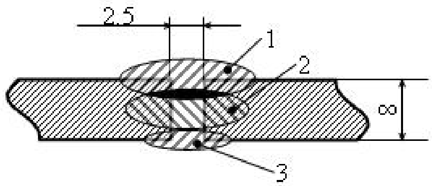

Fig. 5 Deposition mode of the layers (1, 2 and 3) at butt welding for both variants CW and UW.

The technologic parameters of welding (I_w-intensity of welding current; U_w-voltage of welding current; v_w-welding rate; v_d- displacement rate of electrode wire), both at CW and UW, are the same: $I_w = 400$ A; $U_w = 30$ V; $v_w = 5.6\times10^{-3}$ m/s; $v_d = 22.2\times10^{-3}$ m/s.

For the chipped out layer (2), electric current intensity was reduced to 50 %, $I_w = 200$ A.

Table 2. Chemical compositions of the electrode wire, the welding flux and the wire-flux couple after solidification (wt. %)

S12Mn2 electrode wire	C = 0.11 Mn = 2.00 Si = 0.09 P = 0.018 S = 0.027 Cr = 0.08 Ni = 0.26 Cu = 0.26	FB-10 welding flux	SiO_2 = 38 MnO = 10.06 CaF_2 = 4.02 CaO = 20.01 MgO = 8.48 Al_2O_3 = 16.31 TiO_2 = 1.5 FeO = 1.15 P = 0.066 S = 0.036 Humidity = 0.03	Wire-flux couple	C = 0.12 Mn = 1.443 Si = 0.353 P = 0.03 S = 0.019 Cr = 0.043 Ni = 0.057 Cu = 0.147 Mo = 0.019 W = 0.052

Chipping out represents the operation of electric melting with graphite electrode with a diameter of $8\cdot10^{-3}$ m, concomitantly with compressed air blowing in order to remove the remaining slurry from the first layer. After chipping out, the resulting slot was polished to metallic shine before depositing the second layer. Under the above welding conditions, four sets each with five welded specimens were processed designated as *A* in the case of CW and as *B, C* and *D* in the case of UW. The kinematics parameters of the three UW specimens were determined as a function of the ultrasonics frequency (f = 18 kHz) and the vibration length of electrode wire ($l_v = 59\times10^{-3}$m) as summarized in Table 3.

Table 3 Kinematics parameters of UW corresponding to the ultrasonics frequency f = 18 kHz and the vibration length of electrode wire $l_v = 59\cdot10^{-3}m^{(1)}$.

UW1-specimen set B				UW2-specimen set C				UW3-specimen set D			
A	$\bar{v}_v$ (2)	$\frac{v_d}{v_v}$ (3)	A_w (4)	A	$\bar{v}_v$ (2)	$\frac{v_d}{v_v}$ (3)	A_w (4)	A	$\bar{v}_v$ (2)	$\frac{v_d}{v_v}$ (3)	A_w (4)
10^{-6}m	$10^{-2}\frac{m}{s}$	10^{-3}	10^{-6}m	10^{-6}m	$10^{-2}\frac{m}{s}$	10^{-3}	10^{-6}m	10^{-6}m	$10^{-2}\frac{m}{s}$	10^{-3}	10^{-6}m
10	113	19.6	19.4	15	167	13.3	29.9	20	226	9.8	39.4

(1) l_v is determined with relationship (9)

(2) $\bar{v}_v$ is determined with relationship (12)

(3) the ratio $\frac{v_d}{v_v}$ is defined as *relative welding rate*

(4) A_w is determined with relationship (3) considering $A_w = 2A_y$

The experimental oscillation amplitudes A and A_w are controlled by means of a special device equipped with electret-type block with capacitive functions [8, 9]. As noticeable from Table 4, the deviations between theoretical values A_w^{th}, listed in Table 3 and experimentally measured values A_w^{exp}, has been lower than 3 %.

Mechanical tests were performed by means of a VEB WPLM Leipzig/ ZDM tensile testing machine according to EN 10002-1/1995, with a deformation rate of $3.33\cdot10^{-4}$ $m\cdot s^{-1}$. Mechanical characteristics of resistance ($R_{po.2}^{CW,UW}$ - yield stress and $R_m^{CW,UW}$ - tensile strength) and of plasticity ($A_5^{CW,UW}$ - ultimate strain) were determined for both classic and ultrasonic welding, respectively.

Table 4 Comparison between theoretical and experimental values of A_w amplitude of UW corresponding to the ultrasonics frequency f = 18 kHz and the vibration length of electrode wire l_v =59×10^{-3}m[(1)]

Specimen set	$\frac{\bar{v}_v}{v_d}$	A_w^{th}	A_w^{exp}	ΔA_w
	-	10^{-6}m	10^{-6}m	%
B	50.9	19.4	19	2.06
C	75.2	29.9	29	3.01
D	101.8	39.4	39	1.01

4. Experimental results and discussion

In a previous work it was reported that, in the case of tube processing, the use of ultrasonics tends to decrease mechanical resistance and to increase plasticity. The relative variations induced by ultrasonics (UW) as compared to classical technology (CW) were determined as [10]:

$$\Delta R_{p0.2} = \frac{R_{p0.2}^{CW} - R_{p0.2}^{UW}}{R_{p0.2}^{CW}} \quad 100 \tag{13}$$

$$\Delta R_m = \frac{R_m^{CW} - R_m^{UW}}{R_m^{CW}} \quad 100 \tag{14}$$

$$\Delta A_5 = \frac{A_5^{UW} - A_5^{CW}}{A_5^{UW}} \cdot 100 \tag{15}$$

In the present study the same variation tendencies were noticed for $R_{p0.2}$ and A_5, which decreased and augmented, respectively, at UW as compared to CW. Conversely, the values of R_m were augmented by UW.

All the results, comprising displacement and relative welding rates, mechanical characteristics and their variations were summarized in Table 5.

Table 5. Summary of mechanical characteristics and their variations induced by ultrasonics

Speci-men set	CW				UW					Relative variations		
	v_d	$R_{p0.2}^{CW}$	R_m^{CW}	A_5^{CW}	A	$\frac{\bar{v}_d}{v_v}$	$R_{p0.2}^{UW}$	R_m^{UW}	A_5^{UW}	$\Delta R_{p0.2}$	ΔR_m	ΔA_5
	$10^{-3}\ \frac{m}{s}$	MPa	MPa	%	10^{-6}m	10^{-3}	MPa	MPa	%	%	%	%
A	22.2	480	610	8	-	-	-	-	-	-	-	-
B	-	-	-	-	10	19.6	475	612	8.21	1.04	- 0.32	2.55
C	-	-	-	-	15	13.3	460	614	8.32	4.16	- 0.65	3.84
D	-	-	-	-	20	9.8	452	616	8.41	5.83	- 0.98	4.87

Obviously, with decreasing the relative welding rate, $\frac{\bar{v}_d}{v_v}$, yield strength ($R_{p0.2}$) tends to decrease and ultimate strain (A_5) to increase. This effect of applying ultrasonics is consistent with previous observations on steel [10] and aluminium [11]. However, tensile strength (R_m) increased and it is presumed that the main cause for this effect could be the grain refinement induced by ultrasonics during the solidification of the weld. Indeed, for the lowest relative welding rate, $\frac{\bar{v}_d}{v_v}$ = 9.8×10^{-3}, oscillation amplitude has the largest value, A = 20×10^{-6}m, which could cause the most effective fragmentation of primary crystals formed in the weld.

5. Conclusions

A model of the formation mechanism of a stable system of stationary waves during submerged arc welding was developed by considering the kinematics of the displacement and vibration of the electrode wire within the oscillating system. This model allowed deriving relationship (9) for the calculation of the vibration length of electrode wire as a function of ultrasonics wavelength.

The validity of the model was ascertained by laboratory tests, performed by submerged arc welding of naval steel sheets, both with and without ultrasonics. The tests revealed deviations of approx. 3 %., between the calculated and measured values of the maximum oscillation amplitude (A_w) in the forming zone of the electric arc.

As an effect of ultrasonic welding, yield stress ($R_{p0.2}$) decreased and both ultimate strain (A_5) and tensile strength (R_m) increased. Since these variations were larger as the relative welding rate $\frac{\bar{v}_d}{v_v}$ was lower, it was presumed that they could be caused by the increase of the oscillation amplitude of ultrasonics, which breaks primary crystals forming into the weld, thus reducing its grain size.

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*Corresponding author: lgbujor@tuiasi.ro