A unique CEL numerical method on material flow in a molten pool of workpiece vibration assisted welding*

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Workpiece vibration has been applied during arc welding to make weld metal microstructure fine and reduce weld defects such as the blow holes. It was unexpectedly found that the continuous workpiece vibration utilizing a sine component with a specific frequency parallel to welding direction changed the penetration shape from finger-shape to pan-bottom shape in the pulsed metal active gas welding via 18% of CO₂ shielding gas. A coupled Eulerian Lagrangian finite element model was employed especially for adding workspace vibration to the fluid flow of molten materials. The velocity of molten materials through the designated zone of the weld pool was investigated with and without the workpiece vibration. The simulation suggests that increase in the fluid flow velocity along the welding direction at a specific frequency of workpiece vibration led to bringing the high-temperature material to the position where the final penetration shape was determined. Consequently, the penetration bottom would be widened and the middle of fusion line would be deepened, leading to penetration shape change to relatively pan-bottom shape.

Key Words: Workpiece Vibration, MAG welding, Numerical Simulation, Coupled Eulerian Lagrangian (CEL).

1. Introduction

The workpiece vibration is a special type of vibration assisted welding (VAW) procedure to control the microstructure of weld metal (WM) and the heat affected zone (HAZ) 1-2). It is also known for the successful replacement of post-weld treatments for arc welds and many advantages on the process performance of welding. The grain refining, HAZ morphology modification, decreasing the number of blowholes, and reducing residual stresses are the advantages that lead to improving mechanical properties in the weld zone 3). The VAW fundamentally consists of two categories: workpiece vibration and the weld pool oscillation. The molten metal behavior at both cases would help to a mutual understanding of the phenomenon. The molten pool oscillation in the case of gas metal arc (GMA) welding has been studied in the varies point of view over the past years 4-7). These oscillations generally triggered by applying an external force on the weld pool such as superimposing a high current pulse on the welding current or a mechanical vibration of work piece. The irregular movement of the liquid metal is generated by the droplet impingings 8) and the droplets themself are also oscillated due to the interaction of electromagnetic force and the surface tension 9-10). Those make the GMA welding analysis more complicated than the gas tungsten arc (GTA) welding. Several analytical models have been developed for calculating the molten pool oscillation frequency from different viewpoints 11-14). All the models are in agreement with the phenomenon that frequency of weld pool oscillation increased as the surface tension increased, density decreased, and weld pool size reduced. In relatively small weld pools, the surface tension controls the oscillation frequency, while for large weld pools, the gravity and the electromagnetic force control dominantly 11). Past observations on molten pool oscillation have led to the development of oscillation based controlling system to maintain the desired weld penetration during arc welding 15). On the other hand, we unexpectedly found that the finger-shape penetration was modified by applying a longitudinal sine-mode workpiece vibration to the pulsed metal active gas (MAG) welding. The present paper deals with the effect of the longitudinal sine-mode vibration in a coupled Eulerian Lagrangian (CEL) model which designed particularly for adding workspace vibration to the flowing molten metal.

2. Experimental procedure

The welding experiments were conducted using a robotic pulsed GMA welding facility made by KUKA (KR 30-3), controlled remotely by the KR-C2 controller. A mixed gas of Ar 82% - CO₂ 18% was used as the shielding gas. The instant current of the electrode was set to 180 A, consisting of the pulsed waveform with a range from 100 to 340 A. The bead-on-plate welding for a length of 200 mm was performed in a flat position with the contact tip to work distance of 20 mm. The welding speeds were set to 0.6 and 0.7 m/min, and droplets were stably transferring into the molten pool. The base material used in the present work was a hot rolled low carbon steel IS 2062-2011 consisting of the ferrite-pearlite structure. The material for wire electrode was copper coated steel (ER70-S) with a diameter of
1.2 mm. An electro-dynamic vibration shaker of 1500 kgf capacity was used to generate the vibration. The slip table connected to the shaker head was vibrated longitudinally and the fixture was bolted to the slip table with an insulative sheet. A graphical summary of the welding set-up and equipment to be performed is shown in Fig. 1.

![Welding set-up and robotic instruments used as a vibration assisted welding machine.](image)

**Fig. 1** Welding set-up and robotic instruments used as a vibration assisted welding machine.

The cross-sectional macroscopic observation of as-welded specimens were conducted using optical microscopy (OM) after polishing and etching by 7vol% HNO₃ + 93 vol% CH₃OH. To characterize the WM penetration shape quantitatively, curvature of the fusion line was estimated by fitting a circle adjusting its radius to a curved fusion line in the OM image in error by less than 0.2 mm (3N repetition) for the specimens with (w/) without (w/o) longitudinal sine-mode vibration. The frequency values of 250 and 320 Hz at the fixed acceleration of 1.2 m/s² were selected for modeling based on the cross-sectional optical images of specimens obtained in the frequency ranges from 200 to 450 Hz. The correlation of variables is indicated in Eqs. (1) and (2):

\[ x = \frac{D}{2} \sin(2\pi f t) \]  
\[ G_p = 2D f^2 \pi^2 \]

where \( D \) is peak to peak displacement (i.e. \( D/2 \) is amplitude), \( f \) is vibration frequency, and \( G \) is acceleration. The acceleration reaches to a peak \( (G_p) \) in \( \sin (2\pi f t) = 1 \) (Eq. 2).

3. Modeling

A three-dimensional CEL model was developed and solved using the explicit method in Abaqus commercial software. This simulation focused on a part of molten material flow shown by a thin rectangular parallelepiped with a large XY area located in the center of a molten pool, whose position is equal to the central YZ plane as shown in the inset schematic illustration of Fig. 1. The geometry and the meshed model of the rectangular parallelepiped is shown in Fig. 2(a). The Lagrangian shell was defined as molten liquid including a dummy volume in the Eulerian domain that is equal to the rectangular parallelepiped. The lower section of dummy was considered to be a curved shape to help to the pseudo-laminar flowing of material and increasing accuracy of the analysis. The white solid curved line is defined as a liquid-solid boundary. The Lagrangian shell shape supports the minimum sloshing while molten metal turns at the molten pool bottom. That is in good agreement with the experimental phenomenon in longitudinal cross section. The Eulerian domain was generated in a rectangular shape with a volume of 5×6×1 mm³, and it has meshed through 15360 linear hexahedral elements (EC3D8R volume element to model Eulerian problems). Note that the material flowed through the mesh without the movement of the domain element. The specific Eulerian domain was designed to identify molten material flow in the longitudinal cross section of the workpiece at the center of YZ plane during applying the vibration. The molten material flowed by gravity reaches to a peak speed in the laminar flow condition, and continued to flow along the liquid-solid boundary before returning to the topmost zone of molten pool. The molten material flow in the window surrounded by a broken line in Fig. 2(b) was mainly analyzed during the simulation based on the comprehensive computational fluid dynamic (CFD) analysis results 16). The velocity of molten material flow was obtained at the probe position in the window for welding conditions w/ and w/o vibration, for comparison.

Assuming that the simulation steps were divided into initial, intermediate, and final steps (located around front, central, and rear YZ planes) in a Lagrangian shell in Figs. 2(a) and 2(b), they correspond to phenomena exhibiting droplet impinging, fluid flow of molten materials, and starting solidification, respectively (Please see Figs. 1, 2, and 3(a)). In this simulation, the intermediate step of molten material flow was focused on.

The setting operation of flowing-molten-metal model was simplified focusing on the gravity force, longitudinal...
displacement and low friction boundary, while the heat transfer was ignored due to the short process time. The effect of other forces such as the electromagnetic force were covered by kinematic energy and momentum close to the experimental condition, simulated in a special Eulerian dummy volume (Fig. 2(a)). It should be noticed that all the input data such as instant velocity and flowing direction around 20 ms were extracted from the results of CFD analysis on the finger-shape penetration using welding parameters relatively similar to this study. A tangential behavior was considered in the penalty mode with 0.05 friction coefficient while the normal behavior followed the hard contact property. The molten metal density, the equation of state coefficient in us-up mode, and the dynamic viscosity were set to 7000 kg/m³, 4780 m/s, and 0.005 kg/m.s respectively. The frequencies of longitudinal vibration were adjusted to 250 and 320 Hz within 0.5 and 0.3 m of amplitude, respectively.

4. Results and discussion

The cross-sectional OM images obtained from the center of the as-welded plates are shown in Fig. 3. In the specimen w/o vibration, a finger-shaped penetration was obtained with 1.03 rad/mm in curvature of the fusion line (Fig. 3(a)). Applying a continuous longitudinal vibration with the frequency range from 200 to 450 Hz varied the penetration shape in a relatively similar depth. A gently curved penetration with the smallest curvature of 0.45 rad/mm was obtained in the specimen w/ vibration at 320 Hz, as shown in Fig. 3(c). A curved penetration with intermediate curvature of 0.68 rad/mm was obtained in the specimen w/ vibration at 250 Hz (Fig. 3(b)). Similarly, the intermediate curvature of 0.68 rad/mm was obtained in the specimen w/ vibration at 350 Hz. It was considered that the specimen is suitable for analysis of the phenomena which helps to clarify the mechanism of penetration shape change.

The fusion lines of three specimens can be divided into two parts near the weld toe and bottom. Slope of both the parts of fusion line was quite different in the specimen w/o vibration (Fig. 3(a)), and was getting to be similar in the specimen w/ vibration at 250 Hz (Fig. 3(b)). Consequently, the difference almost disappeared in the specimen w/ vibration at 320 Hz (Fig. 3(c)), leading to relatively pan-bottom penetration shape. The slope at a half of fusion line near the weld toe did not change so much as a frequency increased, in contrast to another half of fusion line near the weld bottom moved toward a base metal in a Z direction, resulting in the gentlest slope at 320 Hz.

In order to proposing a reliable mechanism on the penetration shape change, the interaction of all forces in the weld pool must be understood. Cheon et al. modeled a CFD based analysis on the finger-shape penetration with tracking the molten droplet momentum in the longitudinal cross section of weld pool. According to the CFD analysis, the impingement momentum of the droplet was maintained at the molten pool bottom, resulting in the formation of a deep finger-shape penetration. The localized droplet momentum at the velocity of 180 mm/s disappeared about 20 ms after the formation of the deep penetration. The material continued to flow backward at a deep level of the molten pool as marked by num. 1 in Fig. 3(a) and finally return to an upper level. The following movement path in the molten pool was considered to be those marked by num. 2 and 3 in Fig. 3(a), in order.

The vibration effect on the fluid flow of materials in the molten pool was investigated in more detail using the modeling as shown in Fig. 2. The thin simulation domain was located along the XY plane at the center of weld bead, matching with the fluid flow of num. 1 in Fig. 3(a). Time variation of velocities in the X direction and in magnitude of molten materials at the probe position corresponding to the central position of flow (Fig. 2(b)) for the specimen w/ vibration at 250 Hz, marked by \( V_x \) and \( V_m \), respectively is shown in Fig. 4, together with those w/o vibration. The velocity of fluid flow material w/o vibration in the intermediate step between 20 and 27 ms was consistent with that obtained in the CFD analyses. Noted that the time range from 0 to 20 ms in the CEL process was related to generating the intermediate step and still far from the weld pool condition in the CFD analyses, therefore, we omitted the time range from Fig. 4.
and similarly from Fig. 5. The values of $V_x$ increased significantly between 21 and 22 ms in the specimen w/ vibration at 250 Hz in comparison to those of the specimen w/o vibration, and the value reached to the maximum just after 22 ms. The values of both specimens w/ and w/o vibration were almost similar after 23 ms, while the early advent of sudden decrease around 26 ms occurred in the specimen w/ vibration. Difference of trends of $V_m$ time variation between both the specimens maintained similar to those of $V_x$, except in the beginning of time region where velocities in the Y direction ($V_y$) was contributed to $V_m$ more than $V_x$. The contribution of $V_y$ to $V_m$ seemed to disappear until 22 ms. Note that values of velocity in the Z direction ($V_z$) was insignificant contribution to $V_m$ at the designated zone, since the thickness of model was very thin in comparison to other dimensions.

The time variation of velocities for the specimen w/ vibration at 320 Hz is shown in Fig. 5. The values of $V_x$ and $V_m$ observed in the time range between 20 and 22 ms were higher in the specimen w/ vibration than those in the specimen w/o vibration. It was similar to those obtained in the specimen w/ vibration at 250 Hz, while the amount of velocity increase became larger. The $V_y$ increase started 0.5 ms earlier than the specimen w/ vibration at 250 Hz, and consequently the increase of $V_m$ between 21 and 22 ms was larger. In addition, the $V_m$ increase seemed to include both the contribution of $V_x$ and $V_y$ in contrast to that in the specimen w/ vibration at 250 Hz. It suggests that the high-momentum droplets, which also exhibited higher temperature, remained for a certain time in the fluid flow in the X direction to the rear YZ plane behind the probe position before being caught up in flow dynamics of the weld pool in the specimens w/ vibration at 250 Hz and furthermore w/ vibration at higher frequency of 320 Hz. In addition, it was expected that some of the droplet contents with high momentum return to the top surface and followed by moving to the Z direction as shown in Fig. 3(a). Based on further studies in the specimens w/ vibration at frequencies, e.g., the values of $V_x$ between 21 and 22 at 400 Hz exhibited almost the same increase in the specimen w/ vibration at 250 Hz (Fig. 4(a)). It suggests that the sine vibration along welding direction enhanced values of $V_x$ in the time range between 20 and 23 ms and the frequency of 320 Hz maximized the increase of $V_x$. This would be related to the smallest curvature in penetration shape at 320 Hz (Fig. 3(c)) in the frequency range between 200 and 450 Hz.

A final penetration shape, comparable to that in the rear YZ plane, is suggested to be generated by the superposition of front, central, and rear YZ planes. The penetration bottom depth would be determined by the central downward fluid flow in the front YZ plane. The penetration bottom width and curvature of the middle part of fusion line would be determined by both the remaining fluid flow in the X direction and a side vortex of molten materials related to returning fluid flow to the top surface as shown in Fig. 3(a). The similar $V_y$ was estimated at the initial time region in Fig. 4 and 5 in the three specimens, upon impingement of the droplet. This is in good agreement with the similar penetration depth observed in the three specimens. This suggests that the longitudinal vibration cannot affect the downward momentum of
droplets. On the other hand, the vibration enhanced the backward momentum of droplets in the X direction. This suggests that the fluid flow of materials to the rear YZ plane behind the probe position increased (widening the penetration bottom width), in addition to increasing fluid flow materials that returned to an upper molten pool and followed by toward weld toes. The increase of fluid flow toward the weld toe would enhance the side vortices near the weld toes. This would result in applying downward pressure at the middle part of fusion line. This would lead to a new dynamic equilibrium condition, as shown in Fig. 3(c) (yellow arrows) in comparison to Fig. 3(b).

Note that the similar time scale was not able to obtain in the CEL and CFD analyses, although many parameters were justified to obtain the same value of velocity at the probe position in the specimen w/o vibration in both the analyses. It was associated with simplifying the model and ignoring force interaction. In CEL analysis with the time range between 0 and 35 ms, for example, the velocity value exhibited a deviation from that obtained from CFD analysis in the time range more than 27 ms when molten pool reached to the upper part of the left shoulder in Lagrangian shell as shown in Fig. 2(a). Similarly, the molten materials were not located in the corresponding position in the welding condition in the time range before 20 ms. Thus, the candidate time period between 20 and 27 ms was taken for the CEL analysis in cooperation with the CFD analysis, and the velocity obtained at the probe position from both the CEL and CFD analyses was consistent. This time range in the CEL analysis corresponded that between 0 and 20 ms in the CFD analysis. The difference of total time range can be acceptable assuming that the probe position in CEL analysis was located near the center of molten pool where the molten materials move in a short time for a short moving distance at the same velocity, in comparison with the position near the boundary of molten pool. The probe position in CFD analysis was located near the boundary of molten pool.

**Conclusions**

A localized CEL numerical model was developed successfully based on a comprehensive CFD analysis to investigate effect of workpiece vibration on the penetration shape change. The workpiece vibration parallel to the welding direction increased $V_s$ of molten material flow in an early stage of the intermediate step. The increase maximized at vibration frequency of 320Hz, and is in good agreement of experimental penetration-shape variation with frequency. In addition, the $V_s$ increase also would expect to increase fluid flow materials returning to an upper molten pool, leading to enhancement of the side vortices near the weld toes. Those suggest widening the penetration bottom width and increasing downward pressure at the middle part of fusion line.

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