Simulation of Thermo-Mechanical Effects Induced by Submerged Double-Arc Welding Process in Pipelines

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Abstract: - The present investigation focuses on the evaluation of heat transfer and von Mises stress distribution in longitudinal welded pipelines performed by multi-pass submerged double arc welding (SDAW). A complex three-dimensional finite element model has been developed in order to simulate the coupled thermal-mechanical fields. Transient and steady-state distributions evolution, prediction of temperature field and evaluation of equivalent stress have been analysed and discussed in detail. Finally, important conclusions highlight the thermal and mechanical effects induced by submerged double-arc welding process in pipelines.

Key-Words: - Pipelines, 3D finite element model, submerged double arc welding, thermal history, stress.

1 Introduction
Submerged arc welding (SAW) is the most applicable and productive procedure when thick sections have to be welded. Welding thick material involves large amount of filler material and, frequently, long length of welds. The process is used for the welding of low carbon steels, stainless steels, nickel-based alloys or surfacing applications. Due to the high value of deposition rate, deep penetration, uniform and aesthetic appearance of welding layers, submerged arc welding is widely applied in manufacturing of pressure vessels, pipelines, ships and offshore structures. Although the process itself is characterized by a high level of productivity, the actual trends in the process development are looking for further growth of the deposition rate. The submerged arc welding process has continuously developed and, presently, can be performed in various ways, from the simplest process with a single wire and DC power to more advanced twin-wire and tandem welding variants. A particular case is that of pipelines used in the transport infrastructure of refined petroleum products. The longitudinal welded pipelines are, most of the time, performed by submerged arc welding procedure with multi-arcs while high productivity is achieved. Still, the quality criterion has to be the highest priority in achievement of safe welded joints. Simulation of the manufacturing process is useful in designing the optimum technology and choosing the best welding conditions which ensure safe and quality welded joints. Finite element analysis programs have evolved and weaknesses in joining technology designing can be detected, even before testing the welded joints. Thermal, mechanical and structural effects induced by the welding process on the base materials are rigorously predicted.

API-5L grade steel is one of the most common pipeline materials. The oil and gas industries have increased need for the use of High Strength Low Alloy (HSLA) steels such as API-5L-X70 and X80, due to the cost savings they afford, especially in long piping systems that transport crude oil or natural gas [10]. The properties related to their mechanical strength, toughness are remarkable. The HSLA steels are usually welded in the as-rolled or the normalized condition, and the weldability of most HSLA steels is similar to that of mild steel [10], [11]. The welding process strongly influences the performances of the metallic structures and their capacity to resist overload. A special attention should be given when HSLA steel is welded and used for gas transport pipelines. The welding variables and the material properties affect the temperature profiles, stress and strains level, microstructure and, finally, the performances of the welded joint. In conclusion, the welding effects should be minimized in order to preserve the special features of this steel grade, such as fine-grained achieved due to the presence of nitrides and/or carbides, finely distributed, high strength and high resistance to brittle cracking [5], [6], [8], [12].
Finite Element Analysis of SDAW

Deteriorating of the mechanical properties in the weld zone and heat affected zone (HAZ) of the welded structures has become a major concern of all experts and practitioners involved in steels welding industry. The complex nature of thermal, physical and chemical phenomena developed in the space of the electric arc, in the welding pool and around it, generates thermal, metallurgical and mechanical effects that produce the worsening of pattern material properties. Non-uniform expansion and contraction of the weld metal and adjacent areas - by heating and cooling cycles induced by the welding process - cause the development of thermal stresses in these regions. During the heating phase, the strains induce plastic deformation of the metal. The stresses resulting from these strains combine and produce internal forces that cause a variety of welding distortions. Therefore, an accurate prediction of stress and strain fields is needed in the estimation of integrity and safety level of welded structures achieved in real welding conditions.

Nowadays, submerged multi-arc welding is more and more applied to the pipelines manufacturing due to the increased productivity and efficiency of the process in comparison with the classical submerged arc welding. Still, the productivity increasing should be limited to preserve the mechanical characteristics of the base material. Due to this reason the heat input should be limited or preferably distributed on multiple arcs. In this way, applying multiple submerged arcs the advantages of qualitative welded joint achievement and increased productivity are combined.

This paper focuses on the investigation of heat transfer and evaluation of Von Mises stress distribution in longitudinal welded pipeline performed by multi-pass submerged double arc welding (SDAW). The research was focused on the submerged arc welding applied in two distinct welding pools variant. A three-dimensional finite element model was developed to simulate the coupled thermal-mechanical field.

In modelling of welding process, the heat source is often considered an ellipsoidal model. Goldak et al. proposed a semi-ellipsoidal heat source and further improved into a double-ellipsoidal source in which the heat flux is distributed in a Gaussian manner throughout the volume of two semi-ellipsoids, as figure 1 shows [4].

The governing equation for transient heat transfer analysis is given by Eq. (1) and the spatial heat distribution which is different in front and in the rear of the thermal source can be computed by applying the equations (2) and (3) [1]:

\[
\rho \cdot c \cdot \frac{\partial T}{\partial t}(x, y, z, t) = \nabla q(x, y, z, t) + Q(x, y, z, t)
\]

(1)

\[
q_f = \frac{6\sqrt{3} \cdot \eta \cdot Q \cdot f_f}{\pi \sqrt{\pi} \cdot a \cdot b \cdot c_f} \cdot \exp\left(-3\left(\frac{x^2}{a^2} + \frac{y^2}{b^2} + \frac{z^2}{c_f^2}\right)\right)
\]

(2)

\[
q_r = \frac{6\sqrt{3} \cdot \eta \cdot Q \cdot f_r}{\pi \sqrt{\pi} \cdot a \cdot b \cdot c_r} \cdot \exp\left(-3\left(\frac{x^2}{a^2} + \frac{y^2}{b^2} + \frac{z^2}{c_r^2}\right)\right)
\]

(3)

where: \(a, b\) and \(c\) are the ellipsoidal heat source dimensions; \(c_f, c_r\) - heat source dimensions in front and rear of semi-ellipsoid; \(f_f, f_r\) - coefficients of heat apportionment in front and in the rear of semi-ellipsoid (\(f_f + f_r = 2\)); \(q_f, q_r\) - heat flux in front and in the rear of heat source; \(Q\) - heat input (\(Q = \eta \cdot U \cdot I\)); \(U, I\) - welding voltage and amperage; \(\eta\) - welding process efficiency.

In order to simulate the butt SDAW, two ellipsoid models with different dimensions have been considered in the complex model. An X-joint of two API-5L-X70 steel plates, with similar dimensions (19.1x250x800 in mm), have been considered in the pattern. The joint is welded on both sides, being named top and bottom of joint. The time needed to rotate and prepare the joint for welding on the other side is 10 min. A non-uniform mesh pattern with SOLID7 elements was generated (Fig 2). A fine mesh was built along the longitudinal axis to cover the main areas of the joint – welding pools, heat affected zone (HAZ) – which are strongly affected by the process. Isotropy of the base metal, thermo-physical properties depending on temperature and latent heat have been considered in the numerical model. Heat flux losses by convection and radiation have also included in the heat transfer model. The initial temperature of the steel sheets was considered 20°C in the modelling and simulation of SDAW.
The welding speed is supposed to be constant during the whole process. The heat input is kept constant whilst the welding source continuously moves, heating and melting new regions in front of it, and maintains its influence on the welding pool, as too. In order to simulate the sources' movement along the longitudinal axis of the joint, two time functions - corresponding to each heat source - were developed as a succession of triangle functions. The temperature field is a result of the total thermal effects generated by both heat sources, from the initial moment of the process \( t=0 \) until the final moment \( t=t_n \) [9].

On each side of the longitudinal joint, the welding process can be described in three phases:

- **Starting phase**: first welding source begins the welding process, performing the first layer of joint;
- **Intermediary phase**: after first thermal source moves 100 mm along the longitudinal axis, the second welding source starts to completely fill the groove (Fig.3);
- **Final phase**: first welding source finishes the first layer and leaves the steel sheets. The second welding source continues the welding process until the joint on the one of sides is complete.

According to the notations from the sketch illustrated in figure 4, data related to \( a, b, c_f, c_r \) specific to the SDAW pools have been introduced in the numerical model, as table 1 shows below.

**Fig.3** Sketch of the SDAW intermediary phase

**Table 1** Input data for simulation of SDAW

<table>
<thead>
<tr>
<th>Dimensions of heat sources [mm]</th>
<th>Location on surface</th>
<th>Welding Arc</th>
<th>Amperage [A]</th>
<th>Voltage [V]</th>
<th>Welding speed [m/min]</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>Top</td>
<td>WA 1</td>
<td>890</td>
<td>36</td>
<td>0.75</td>
</tr>
<tr>
<td>b</td>
<td>Top</td>
<td>WA 2</td>
<td>690</td>
<td>36</td>
<td></td>
</tr>
<tr>
<td>( c_r )</td>
<td>Bottom</td>
<td>WA 3</td>
<td>890</td>
<td>35</td>
<td>0.75</td>
</tr>
<tr>
<td>( c_r )</td>
<td>Bottom</td>
<td>WA 4</td>
<td>690</td>
<td>35</td>
<td></td>
</tr>
</tbody>
</table>
The process is modelled as a 3D heat transfer problem, following the steps described below [8]:

- Designing of sheets geometry and mesh;
- Assembly of element equations;
- Describing of boundary conditions;
- Solving of elements equations;
- Processing of numerical results.

Based on heat conduction, convective and radiative boundary conditions, transient and non-linear thermal solution is solved in order to achieve the nodal temperature history. The temperature field is further considered as thermal loads in subsequent elastoplastic structural analysis to obtain the transient and residual stress fields and distortions. Temperature – dependent thermo-physical and structural properties - conductivity, specific heat and mass density, Young’s modulus, Poisson’s ratio, thermal expansion coefficient, yield strength and strain-hardening rate - are used as input data in the numerical analysis. Phase changing has been included as latent heat in the modeling of SDAW.

4 Results and Discussions

At the beginning of the process, due to the low temperature of the plates and the instability of the process, heat affected zone (HAZ) is less extended. In the steady-state known as the equilibrium phase, the welding process is stabilized and the temperature field has the same dimensions and shape in each moment. In the areas of the heat sources, the temperature gradients are high, involving a specific behaviour of the base material and an alteration of its mechanical and metallurgical properties.

The captures of the temperature field - both on top and bottom of joint – specific to the steady-state of the process are shown in the figure 4. Two distinct welding pools are generated by the heat sources during SDAW. The role of the first heat source is to perform the first weld layer, but plays also a preheating one of the parent material which will be heated and melted again by the second welding source. Once the groove is filled, the joint is turned over, ten minutes free cooled and then the welding process is similarly repeated. The peak temperature (2095.94°C) is reached on the top of joint and matches with the results achieved by other investigators [2], [3]. An insignificant difference of 45°C between the maximum temperatures reached on the top and bottom of joint was noticed, which is an explicable phenomenon due to the cooling of joint made between welding of top side and bottom side. Applying SDAW process, heat is differently generated and distributed in comparison with classical SAW. Consequently, a heating-cooling-heating-cooling particular thermal cycle is developed during the joining process. The numerical outputs were processed and temperature vs. time charts for 19606, 19626, 19627, 80194 nodes, located at different distances from the longitudinal axis of joint, were plotted, as figure 5 illustrates. The only node which was subjected only to a simple thermal cycle is positioned in the weld reinforcing. This is because at the beginning of the welding process it “belonged” to groove and started to be influenced and heated when the second heat source approaches. The other nodes which belonged to the base metal, from the beginning of the welding process, are subjected to a double thermal cycle described by a heating-cooling-heating-cooling complex cycle. When the first heat source approaches these nodes, the temperature begins to increase and reaches the maximum value when welding source is closest to them. Then, first source moves away and first cooling phase starts and lasts few seconds. After that, due to the approaching of the second heat source, the temperature increases for the second time. The process may be considered as a self heat treatment with beneficial effects on the final structure of the welded joint, especially in HAZ. The peak temperature is reached in the heat source’s centre because of the arc highest influence.

Fig.4 Temperature fields on both sides of the welded joint
Captures of Von Mises equivalent residual stress fields on top and bottom of the welded joint are presented in figure 6. Von Mises stress is developed due to different temperature profiles on the inner and outer surfaces of the pipeline. According to Von Mises criterion, failure occurs when the equivalent stress $\sigma_{eq}$ exceeds a critical value. The evolution of $\sigma_{11}$ and Von Mises stresses at different time steps of SDAW process is illustrated in figure 7. Welding similar metals, $\sigma_{11}$ and Von Mises stresses profile is symmetric about the longitudinal axis of the welded joint. The presence of tensile and compression stresses depend on the moment of welding process. If the pool is melted, then compression stress occurs in this area and around it and tensile stress far away ($t=50s$). But, if the pool starts to solidify, tensile stress is generated in the weld and in its vicinity and compression stress far away from these regions ($t=60s, 70s, 80s, 90s$). On the other hand, it can be noticed that Von Mises stress approaches the zero level in the deposited melted metal and increases in HAZ when the welding pool is not solidified. After solidification of the welding pool, the profile shows a maximum level of Von Mises equivalent residual stress near the weld and its vicinity. From chart presented in figure 7, the HAZ extent may be estimated as $20 - 25$ mm. The peak value of Von Mises residual stress is about $393$ MPa.
5 Conclusions
A complex 3D finite element model of longitudinal butt welded joint performed by SDAW was developed and described in this paper. Heat transfer, $\sigma_{11}$ and Von Mises stresses were analysed and discussed. Particular features have been noticed when SDAW is applied to join similar materials:

- The role of the first heat source is to perform the first weld layer, but plays also a preheating one of the parent material which will be heated and melted again by the second welding source.
- A specific heating-cooling-heating-cooling complex cycle is developed during SDAW.
- The presence of tensile and compression stresses depend on the moment of welding process. If the pool is melted, then compression stress occurs in this area and around it and tensile stress far away. When melted pool starts to solidify, tensile stress is generated in the weld and in its vicinity and compression stress far away from these regions.
- Von Mises stress approaches the zero level in the deposited melted metal and increases in HAZ when the welding pool is not solidified. After solidification of the welding pool, the profile shows a maximum level of Von Mises equivalent residual stress near the weld and its vicinity.

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