New Welding Process in the Manufacturing of UOE Pipes*

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Synopsis
A new welding process has been introduced in the manufacture of large-diameter UOE pipes at the Kimitsu Works, Nippon Steel Corp. The new process includes the following methods which have been developed on the basis of fundamental research.

1. Observation of molten pools by X-rays was made during welding to find effective means for the prevention of undercuts. Multiple electrode welding is successfully applied to prevent the undercuts because of its dispersion of the arc in the direction of welding line.

2. Four wire welding has been adopted in place of three wire welding to increase the welding speed without loss of the toughness.

3. Metal inert gas welding can be combined with submerged arc welding to manufacture the line pipes for low temperature service.

4. A flux cored tubular wire with multi-type flux is used for large heat-input welding.

I. Introduction
Recently, pipe manufacturing technology has made a remarkable progress, particularly in the integrated manufacturing technology, including 3 processes preceding the UOE mill; refining, solidifying and rolling which produce the steel for UOE pipes.

Welding is the main process at the UOE mill and the changes in its equipment, welding materials and the operational technique has been quite significant. This paper summarizes the progress made in the processes preceding the UOE mill and describes the advanced welding technology at the UOE mill in detail.

II. Progress in the Manufacture of Steel for Line Pipes
Requirements for the line pipe performance, such as high strength, high toughness and excellent performance in corrosive environment as represented by HIC resistance and SSC resistance have become increasingly severe.

These requirements stem mainly from changes in social and economic situations, such as the change of areas where energy resources are produced, the necessity of utilizing resources of poor quality, and changes in the method of recovery of such resources.

To meet these requirements, the development of integrated manufacturing technology has been promoted. As a result, the production of very pure steel slabs with little center segregation has been made possible by systematically combining dephosphorization, deoxidization, degassing or [Ca] treatment in the refining and solidifying processes with a controlled solidifying process in continuous casting. The purity which can be attained in these processes is expressed in terms of [P] and [S] levels in the molten steel. Generally, the level of [P] is below about 0.005 % and that of [S] is less than 0.002 %. These levels should be attained to meet the above requirements.

The performance of heavy plates for line pipes depends widely on the conditions at the subsequent rolling process. Formerly, plates for high-strength, high-toughness line pipes were produced by controlling the precipitation and recrystallization during rolling by the so-called controlled rolling in which the temperature and pass schedule are optimized. This technique has been further developed into the thermo mechanical control process (TMCP) by adding a controlled cooling. With the TMCP, the strength of plate has been increased and its microstructure has been made more homogeneous, leading to better pipe performance in a corrosive environment.

The function of each process and the process flow for the production of very pure steel are shown in Fig. 1.

TMCP permits the production of high-quality plate with a good shape and excellent properties by the use of restrained-type cooling equipment and a highly advanced computer control system. The heavy plate thus produced is processed into a line pipe through the main processes of the UOE mill, such as forming, welding and expanding.

III. Welding Technology for the Manufacture of Line Pipes
With the development of the steel for line pipes which meets the requirements described previously, technological innovations in the welding process at the UOE mill have been made. Some of the techniques developed recently are introduced below.

1. Multi-electrode Submerged Arc Welding Process
1. Prevention of Undercut
For the increased pipe production, it is necessary to increase the welding speed which has been a bottleneck in the pipe production. Moreover, the increase in welding speed must be attained without impairing weld quality. The submerged arc welding (SAW) has been widely employed for pipe manufacturing because of high efficiency and excellent weld quality. The improvement of this process is underway so as to meet the above requirements by employing higher
current and multiple electrodes.

The most typical welding defect incurred when the welding speed is increased is the undercut. It is considered that the occurrence of welding defects is closely related with the behaviors of welding arc and weld pool. Much work has been directed toward this relation. However, little fundamental work has been done on the multi-electrode submerged arc welding.

Unlike the arc welding, the phenomena occurring during submerged arc welding cannot be visually observed. The welding phenomena have been observed by the RI tracer method, X-ray fluoroscopic method, direct observation method, etc. The X-ray fluoroscopic method is the most effective means as it is capable of analyzing the welding phenomena dynamically.

Figure 2 schematically shows the equipment used for the analysis of the phenomena occurring during multi-electrode submerged arc welding. By this equipment, welding phenomena can be observed by X-ray fluoroscopic method and welding conditions can be changed by the external signal up to 4 electrodes SAW.

In this welding phenomena analyzer, a L-shaped specimen mounted on a carriage was placed between the X-ray tube and the image intensifier as shown in Fig. 2. Welding was performed above the test specimen and arc was formed over the top surface of the vertical portion of the specimen. The image of weld by X-ray produced on the image intensifier was observed by a TV camera and recorded by a VTR. Moreover, the behavior of the weld pool was measured by connecting the VTR to the image processor.

In high-speed submerged arc welding, undercuts are formed when the molten pool has receded from the solidification point along a toe of the weld pool at the back side of the arc. Accordingly, the length and the frequency of the undercut can be evaluated in terms of the relation between the solidification point along a toe of the weld pool (Xs) with the arc point as the starting point and the receding distance of molten metal (Xm). Xs is changed regularly depending on the welding conditions, such as energy input and the initial temperature of steel, and is determined by the thermal conductivity equation for moving heat source. On the other hand, Xm is changed irregularly in a complicated manner depending on the welding conditions, welding flux used, etc. Accordingly, Xm is determined only by a measurement.

Figure 3 shows the relation between the welding speed, the receding distance of molten metal (Xm') and the ratio of undercutting length to welded length in four-electrode welding with an input power of 150 kW. It will be noted that both Xm' and the ratio of undercutting length increase with increasing welding speed. At the same time, the movement of the molten pool becomes vigorous.

Based on the results described above, it was con-
confirmed that little undercut is caused when \( X_{m'} \) is smaller than 10 mm. The same tendency was observed in the one- and three-electrodes welding processes in which the input conditions differ from those in the four-electrodes welding process. It was found that the ratio of undercutting length can be analyzed nearly completely by observing only \( X_{m'} \) even if \( X_s \) is varied to some extent.

Photograph 1 shows examples of the beads formed by the one- and three-electrodes welding processes. It will be noted that there is a considerable difference in \( X_{m'} \) between the two processes on welding conditions for a comparable penetration. Accordingly, the use of multiple electrodes contributes to the reduction of \( X_s \) and the prevention of undercut. This effect may be attributed to the dispersion of the arc force and linearized arc distribution along welding direction due to the adoption of multiple electrodes.

However, even the four-electrodes welding process has its limits in the speed increase. If the welding speed exceeds 3 m/min, it becomes difficult to form the bead which is free from undercut, while securing the required penetration. Photograph 2 shows an example of the bead formed by the four-electrode welding process. At present, a study is underway on the development of welding technology which can further decrease \( X_{m'} \).

Figure 4 shows the relation between the number of electrodes and the welding speed in multi-electrode welding. This relation was determined based on the results obtained from practical applications. It will be apparent from Fig. 4 that the welding speed can be considerably increased by the adoption of multiple electrodes.

2. Toughness of Weld Metal

When putting a multi-electrode welding process into practice, not only the soundness of the weld metal but also the performance of the weld metal, particularly toughness, must be exactly evaluated. In the submerged arc welding process, the performance of welding flux is important in relation to the toughness of the weld metal. In this section, the effect of 4 electrodes on the toughness of the weld metal is discussed.

As well known, the high toughness of the weld metal is achieved by the suppression of precipitation of proeutectoid ferrite, the refinement of structure, and the improvement of purification. In this regard, attention should be turned to changes in the oxygen and nitrogen contents of the weld metal with changes in the number of electrodes. Figure 5 shows the relation between the oxygen content of the weld metal and the heat input in multi-electrode welding. It will be seen that the oxygen content in four-electrode welding does not differ much from that in three-elec-
trode welding.

There is an example\(^{12}\) in which the oxygen content of the weld metal increased with increases in the number of electrodes and welding speed. However, a generalized conclusion cannot be drawn. If the wall thickness is the same, both three- and four-electrode welding can be carried out with the same heat input. Accordingly, there is no substantial difference in oxygen content between the two welding processes.

On the other hand, it is well known that the nitrogen contained in the weld metal has an adverse effect on the toughness of the weld metal. In submerged arc welding, the factors exerting an influence on the nitrogen content include not only the wire and base metal forming the weld metal but also the composition and physical properties of the flux used. Moreover, the influence of welding conditions cannot be ignored.

Figure 6 shows the nitrogen content of the weld metal in four-electrode welding in comparison with that in three-electrode welding. It will be noted that there is no noticeable difference under the welding conditions which are widely employed in practice.

The welding technology for pipe manufacturing has been described above on the basis of the results of analysis of the multi-electrode submerged arc welding. As described earlier, a great progress has been made in the technology for the manufacture of steel for line pipes. Table 1 gives an example of the joint performance of the line pipe made of the plate produced by the most advanced steelmaking technology and welded by the multi-electrode submerged arc welding process. This is an example of the line pipe which can meet recent severe requirements. The combination of such excellent steelmaking and welding technologies has made it possible to produce X-70 grade line pipe with high toughness at a temperature of \(-45^\circ C\).

To meet requirements for still higher toughness of the weld, the reduction in oxygen content of the weld metal is indispensable. For this purpose, the basicity of flux should be increased. If the basicity of flux is increased, however, the workability is decreased at high welding speeds. As a reduction in welding speed is not allowed, it is important to develop a welding material that can meet the requirements for both high toughness and high welding speed.

2. MIG-SAW Process

In the submerged arc welding process described in Sec. III. 1, single run welding is performed from inside and outside of the pipe. In the welding of a heavy-wall pipe, therefore, a large heat input is required. Accordingly, the low-temperature toughness of the weld, including the heat-affected zone, obtained by this welding method is limited. The MIG-SAW process described below is a pipe welding process developed for the application to heavy-wall pipes requiring high toughness in low-temperature service.

The principle of the MIG-SAW process is shown in Fig. 7. This process is characterized in that the thermal cycle for the weld is controlled by increasing the arc spacing so that the heat input per electrode is reduced to 20~30 kJ/cm. The grain growth in the weld can be suppressed by this control. In this process, plural MIG and the submerged arc welding are combined. In the MIG, the electrode spacing can be easily increased and the submerged arc welding produces the bead of better appearance at the final head, so that a small heat input multi-pass welding is performed in a single run.

This heat source dispersion type welding process has been formally approved by the API (5L) as a pipe welding process and is attracting a wide attention as the welding process applicable to heavy-wall pipes for which requirements for low-temperature toughness are particularly severe.

Figure 8 shows the relation between the welding heat input and the toughness of the heat-affected zone. It will be noted that the heat input must be limited.
in order to secure the required low-temperature toughness. To produce high-quality welded joints effectively at a low heat input, it is necessary to stabilize the welding operation by employing narrow gaps, selecting the conditions most suitable for the MIG process and optimizing the electrode arrangement. For this purpose, several important factors as described below must be satisfied.

As the MIG process is designed mainly for heavy-wall pipes, it is desirable that sufficient penetration is obtained in the first pass and the melting rate at each head, i.e., in each pass is high. Therefore, a process newly developed for such welding with a fine wire,
high current density arc, and high current is adopted.\textsuperscript{13}

The electrodes are arranged in such a manner that the leading weld bead is cooled to a temperature below the $A_t$ transformation temperature and reheated by the second MIG process. Namely, the upper limit of the electrode spacing is decided so that the increase in hardness is suppressed by utilizing the preheat of the leading pass. The same applies to the spacing between the second MIG process and the final SAW process. This will be apparent from the thermal cycle shown in Fig. 7.

To apply this process on the line, it is necessary to develop several mechanisms, systems, etc., not required in a conventional submerged arc welding. For example, a high-accuracy seam tracking mechanism, a method for a flying start of the final submerged arc welding electrode, and a stable high-speed MIG wire feeding system must be developed.

In this process, the gap is narrow and the heat input from each electrode is small, and therefore the cross-sectional area of the welding bead is small. Accordingly, the seam tracking with respect to the groove line must be very accurate. Moreover, in the MIG process, the high-current density arc is fed at a constant speed using a constant voltage source. Thus, small variations in wire extension result in variations in welding current, exerting a large effect on the weld bead quality, such as the penetration. Very accurate extension control is, therefore, required also for the vertical direction. Figure 9 shows an example of welding condition control system in which the wire extension control for maintaining a constant wire extension is incorporated. In this system, changes in welding current due to changes in wire extension are detected and fed back. In addition, a technique for a flying start of the final SAW electrode has been developed.

Table 2 shows an example of the performance of

<table>
<thead>
<tr>
<th>Grade · Size</th>
<th>API 5L-X70, 28° OD x 28mm WT</th>
</tr>
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<tbody>
<tr>
<td>Chemical composition (%)</td>
<td>C</td>
</tr>
<tr>
<td></td>
<td>.05</td>
</tr>
<tr>
<td>Welding condition</td>
<td>Outside welding: MIG-SAW process</td>
</tr>
<tr>
<td>MIG; wire dia. 1.2\textm, 500A, 36V, oscillation 6Hz, 3-6mm</td>
<td></td>
</tr>
<tr>
<td>heat input</td>
<td>21.6 kJ/cm</td>
</tr>
<tr>
<td>SAW; heat input</td>
<td>29.2 kJ/cm</td>
</tr>
<tr>
<td>Inside welding; SAW process, heat input 29.4 kJ/cm</td>
<td></td>
</tr>
</tbody>
</table>

1. Charpy and COD test

<table>
<thead>
<tr>
<th>Test results</th>
<th>v\textsubscript{E-\textacuten} (J)</th>
<th>Weld metal</th>
<th>Bond</th>
<th>HAZ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outside</td>
<td>90.0</td>
<td>93.0</td>
<td>139.0</td>
<td></td>
</tr>
<tr>
<td>Center</td>
<td>224.0</td>
<td>164.0</td>
<td>102.0</td>
<td></td>
</tr>
<tr>
<td>Inside</td>
<td>220.0</td>
<td>116.0</td>
<td>172.0</td>
<td></td>
</tr>
<tr>
<td>COD</td>
<td>$\delta$-60°C (mm)</td>
<td>0.20</td>
<td>0.16</td>
<td>0.15</td>
</tr>
</tbody>
</table>

2. Hardness distribution in weld
the weld joint produced by this welding process. It will be noted that the toughness of this joint at \(-60^\circ\text{C}\) is excellent.

The welding process for pipe manufacturing has been described. This can be applied to heavy-wall pipes requiring an excellent low-temperature toughness. The process has a disadvantage that the welding speed is still considerably low compared with that of the submerged arc welding process. To ensure wide application of this process for pipe manufacturing, therefore, the process should be improved so that the speed can be increased without deteriorating the current quality level.

3. Flux Cored Tubular Wire

In the welding of a pipe, the quality of the weld is greatly influenced by the quality of the welding materials, particularly the flux. In view of this important role of flux, the melt type flux is now widely used. Major advantages of this flux are an easy use in the production line, an easy storage because of a high moisture repellency, and little change in particle size during handling. As this flux is low in melting point and viscosity, it fits the welding conditions of a high speed and a small heat input. The bead appearance becomes worse if the heat input is increased. There is, therefore, a limit to the use of this flux. To produce heavy-wall line pipes to be used under severe conditions, a highly productive one-pass welding on both sides must be developed. Such a welding requires a large heat input.

When the heat input is increased, irregular equiaxed dendrite is formed at the top of the bead and the bead shape becomes irregular as shown in Photo. 3. Namely, in a large heat input welding, a flux with low refractoriness is intermittently blown up in the vicinity of the arc and the flux thus blown up disturbs the steady solidification of the equiaxed dendrite which has become more liable to be formed because of insufficient heat insulation of the bead.

A study was made on the use of the flux cored tubular wire for improving the refractoriness of the molten slag. Conventional tubular wires with seams are low in stability of wire feeding, conductivity and moisture repellency. The use of a seamless tubular wire which is excellent in the above properties was, therefore, studied. In the submerged arc welding using the flux cored tubular wire, (1) the chemical compositions of the core and (2) the selection of optimum welding conditions must be examined.

The use of cores with a high melting point, such as MgO, Al₂O₃ and Zr₂O₃ type cores, was studied. It was found that MgO-CaF₂ type core has the highest bead forming property. If the melting point becomes too high because of a high MgO/CaF₂ ratio, the core is not fully melted in the arc during welding and is entrapped in the weld pool, resulting in slag inclusions. If the MgO content is too low, the bead formation is not improved.

The compositions suitable for the prevention of slag inclusions are shown in Fig. 10. The melting point of the core of such chemical compositions is about 1 800 °C which is lower than the temperature of the weld pool directly below the arc. Even if a core with such melting characteristics is entrapped in the weld pool due to the occurrence of instantaneous shorts, it can be easily separated through flotation.

Photograph 4 shows the melting of the flux cored tubular wires. It is seen that the high MgO type core is not completely molten in the weld pool. With
the wire with high MgO type core, the wire sheath is molten before the core, and the unmelted core is entrapped in the weld pool. This tendency becomes more significant with increasing wire extension, increasing current and decreasing voltage. With the wire with low MgO type core, however, the core is melted into droplets and these droplets are transferred into the weld pool over a wide range of current and voltage.

If a tubular wire is applied to all electrodes in the multi-electrode submerged arc welding process, a good bead shape is obtained but the penetration is insufficient. Sufficient penetration and good bead shape can be obtained by using a solid wire for No. 1 electrode and a tubular wire for the other electrodes. Based on these findings, high-quality pipes with a wall thickness of 40 mm could be produced by the three-electrode method with a heat input of 160 kJ/cm.

The application of the flux cored tubular wire made from seamless tube to the welding of heavy-wall pipes has been described above. This type of wire will find increased application in the future. Recent trend is toward a small lot production of various sizes and grades to meet the diversification of line-pipe demands. It is, therefore, necessary to make available a variety of welding materials of optimum design in small quantities. In this sense, the flux cored tubular wire is an excellent material as it provides flexibility in design.

**IV. Conclusion**

Recent advances in the manufacture of line-pipes and steel plates for the pipes have been described, placing emphasis on the welding of large-diameter pipes at UOE plants as an example of welding at the production site. For the line pipe steel plates, the clean steel manufacturing technology and rolling technology represented by TMCP have been introduced.

Great progress has been made in the welding process, materials and techniques as described below as a result of fundamental research undertaken at the Welding Research Center.

(1) By observing the behavior of the molten pool through X-rays, it was found that the receding distance \(X_{m}'\) of the molten pool increased with increasing welding speed. Based on this finding, it was made clear that \(X_{m}'\) should be maintained below 10 mm to prevent undercuts.

Multiple electrode welding is effective for the prevention of undercuts, because the arc is linearly dispersed in the direction of the weld line.

(2) If three-wire welding is changed to four-wire welding in order to increase the welding speed, the chemical composition of the weld metal is changed little and a difference in the heat input is not noticed. The toughness is practically the same after both weldings.

(3) A single-run, multi-pass MIG-SAW method has been developed for the manufacture of line pipes with high toughness at low temperatures. It is expected that this welding process permits the manufacture of line pipes for service temperatures as low as \(-60^\circ C\).

(4) A flux cored tubular wire with a core prepared by mixing a proper amount of oxide of a high melting point has been developed and used as a material for a large heat input welding. This wire is used together with a melt type flux, and welding with a large heat input of 160 kJ/cm has been made possible.

**REFERENCES**


3) K. Ishizaki: *Welding Technique*, 12 (1964), No. 12, 45-49.


