Some Improvements in Self-Shielded Flux Cored Electrodes for Arc Welding

Weld cross section studies result in minimized gas content and improved weld metal quality, and reduction of Al content improves weld metal toughness

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ABSTRACT. In Japan, self-shielded flux cored electrodes for arc welding are used for outdoor applications in civil engineering, architectural building and shipbuilding. One of the most important aspects examined in this field has been the reduction of the atmospheric gas content to improve the impact toughness of the weld metal.

A fundamental study has been conducted on these aspects over a long period of time. The effect of various factors on arc and gas absorbing phenomena has been elucidated in this study. The study on the cross-sectional shape and size of the electrodes initially provided useful information for improving the quality of commercial electrodes. The gas content could be minimized and the quality of the weld metal improved by making the electrode cross-section more complex and the size as fine as possible. In commercial electrodes, reducing the Al content to improve weld metal toughness was also achieved by adopting a constant potential dc power source together with the results of fundamental research. In addition, both the reduction of welding fumes and the use of surface treatment without hydrogen-forming materials have greatly improved the usability of the electrodes.

Introduction

In Japan the history of flux cored electrodes for self-shielded arc welding, goes back to the early 1960's. At the beginning, this process, mainly for economic reasons, was limited to an ac welding system made up of a combination of a comparatively large size electrode and an ac power supply. After years of research, however, the authors recently perfected a dc welding system using a fine electrode which is more advantageous both in quality and usability than the ac system. The flux cored electrodes for the dc system have also been so improved as to be particularly suitable for onsite welding in civil engineering, architectural building, ship-building and so forth.

The main objective of this paper is to discuss the fundamental research, the improvement of commercial electrodes and applications of typical electrodes recently developed for the dc system. A practical study of commercial electrodes was also conducted to decrease both the Al content and cross-sectional shape of the arc and the welding fumes which are considered major obstacles to more widespread application of this process.

In Japan, the ac system still predominates with regard to the quantity used (Ref. 1). However, the improvements in usability, quality and weldability with fine electrodes have led to an increased consumption of the electrodes for the dc system.

Research on Welding Phenomena

Arc Phenomena and Electrode Transfer

Effect of Cross-Sectional Shape of Electrode. The arc phenomena of flux cored electrodes differ substantially from that of the manual metal arc electrodes. The flux covering of the manual arc electrode is inevitably melted down from the core; this results in a cylinder at the melting end of the electrode. The cylinder facilitates smooth transfer of metal droplets to the workpiece. On the other hand, the unmelted flux cone of the flux cored electrode tends to project into the arc gap and produces considerable spatter and poor reaction between the core flux and the metal sheath. In this case, it is presumed that the metal section of the flux cored electrode is the most important factor in overcoming these undesirable features.

From an examination of the relationship between the melting pattern and cross-sectional view of the electrode, it was found (Fig. 1) that uniform melting of the wire can be achieved when the metal section is more complex, i.e., the melting pattern is improved in the order of electrode (i.e., wire) types O, T and E. The cone of the unmelted flux is clearly silhouetted in Fig. 1, particularly in the case of electrode (wire) O.

The size of the metal droplets is also affected by the electrode cross-section as shown in Fig. 2. The effect of the electrode cross-section on the droplet size for the welding current range 300-500 A, is clarified in Fig. 2. Fig. 2, $d_{50}$ denotes the droplet size at 50% of droplet weight percentage integrated on the graphic relation between integrated weight percentage of droplets and droplet size (Ref. 3). The effect of core flux component. Figure 3 indicates the effect of the flux component on the droplet size obtained by using three kinds of experi-
mental electrodes: B — containing iron powder only; C — titania type flux; and N — strong deoxidizer of CaF$_2$CaCO$_3$ type.

As shown in Fig. 3, there is a great difference between the droplet size, $d_{90}$, of these electrodes. The smallest droplets were obtained from electrode C and larger droplets from both electrodes B and N. Generally speaking, a flux core of self-shielded arc welding electrode usually contains gas-forming materials such as metal carbonates and volatile metals in order to shield the arc from air contamination. A series of tests showed clearly that such gas-forming materials have a considerable effect in making the metal droplets small and causing a spray type mode of transfer.

Figure 4 shows the effect of adding a volatile metal to the flux core on the electrode metal transfer mode, using three kinds of electrodes with different amounts of Mg. In Fig. 4, it can be seen that the droplets of the electrode with high Mg content are blown off by the high vapor pressure of Mg which is explosively formed from its vaporization under the great heat of the arc, causing a spray type of metal transfer. In the case of the electrode with low Mg content, the droplets become bigger because the above effect of the Mg vapor does not occur.

**Fig. 1** — Effect of cross-sectional views of flux cored electrodes on their melting patterns in ac welding (3.2 mm electrode diameter; 2,500 frames/sec photography speed; 400 A welding current; 37-40 V arc voltage) (Ref. 2)

**Fig. 2** — Effect of electrode cross-section and welding current on droplet size, $d_{90}$ (Ref. 2)

**Fig. 3** — Effect of core flux component on droplet size, $d_{90}$ (Ref. 2)

**Fig. 4** — Effect of Mg addition to flux core on electrode metal transfer mode (2.4 electrode diameter; 250 A welding current; dcrp; 2,500 frames/sec photography speed) (Ref. 4)
Effect of Electrode size. The authors have investigated the effect of electrode size on the arc phenomena. Selected results of this research are given in Fig. 5 where some frames of high speed motion cine-photographs are shown. Contrary to the authors' expectations, the smallest diameter electrode did not produce the finest metal droplets. The metal droplets from the large size electrodes are somewhat smaller than those from the finest electrode, as can be seen in Fig. 5.

Effect of Wind. The width of the weld bead deposited on mild steel plate has been shown to decrease with increase in the velocity as the cooling effect of the wind constricts the welding arc, making the bead weld narrower (Ref. 6). However, the authors were unable to achieve the obvious effect of wind velocity on the electrode metal droplet size as reported in Ref. 2.

Effect of Electrical Polarity. Electrical polarity in flux cored electrode welding is one of the factors markedly affecting the arc phenomena. From the experimental results, it is clear that the droplet size can be greatly reduced by straight polarity welding, and is increased with the reverse polarity as indicated in Fig. 6. In ac welding, the arc phenomenon — in other words, metal transfer mode — is rather complicated and is intermediate to those of the two dc polarities. The same effect of electrical polarity as mentioned above is shown for the droplet size distribution.

Absorption of Atmospheric Gas

Effect of Cross-Sectional Shape of Electrode. Although self-shielded welds are reasonably protected from the air contamination by both the slag and the gas from the flux core, it is fairly difficult to prevent atmospheric gases from entering the molten metal and impairing its properties. Therefore, the gas absorbing phenomena of welds should be carefully investigated in order to obtain higher quality from both the radiographic and physical points of view.

Studies relating to the nitrogen content of both the metal droplets and the weld beads from the experimental electrodes of different cross-sections have been reported (Ref. 2). It was observed that the air contamination (in other words, nitrogen absorption of electrode metal) could be appreciably reduced by using a more complex cross-section electrode. This phenomenon may have resulted from the effect of electrode structure on the arc phenomena as discussed previously.

Effect of Flux Core Components. Figure 7 illustrates the marked effect of gas-forming and degasifying ingredients in the flux core on the content of the nitrogen absorbed by the electrode metal droplets. In Fig. 7, it can be seen that the droplets from electrode (or wire) B, with only iron powder, absorb the most nitrogen, because of the absence of any gas shield. In addition, electrode B appears to exhibit the same behavior in nitrogen absorption as solid wire for self-shielded welding, where the nitrogen absorption is markedly af-

Fig. 5 — Effect of electrode diameter on arc phenomena (250 and 450 A welding current; dcrp; 2500 frames/sec photography speed) (Ref. 5)

Fig. 6 — Effect of electrical polarity on arc phenomena (2.0 mm electrode diameter; 250 A welding current; 2500 frames/sec photography speed) (Ref. 7)

Fig. 7 — Effect of flux core compositions on nitrogen content in electrode metal droplets (Ref. 2)
fected by welding current, as reported elsewhere (Ref. 8). On the other hand, the nitrogen content can be more reduced when welding with electrodes (or wires) C and N which were originally designed for the CO₂ arc and the self-shielded arc welding process respectively. In the case of electrode (i.e. wire) N, it can be observed from some of the frames in the high speed cine-film of Fig. 8, that the metal droplets transferring through the arc gap have a vapor blanket of volatile metal (Ref. 9) surrounding them; the vapor blanket is considered to be an ideal shielding medium to protect the droplets from air contamination.

It should be noted that such flux types as ilmenite, lime titanite and iron oxide are apt to pick up more nitrogen and oxygen from the air, compared with the basic CaF₂-CaCO₃ type and commercial self-shielded welding electrodes containing a large amount of Al.

Effect of Electrode Size. As shown in Fig. 9, nitrogen contained in self-shielded weld deposits can apparently be decreased by reducing the electrode size. This may be caused by such combined effects as the increased melting rate of the electrode (due to the reduction in electrode size) which shortens the reaction time between the metal droplets and the atmospheric gas and the reduction of the surface area of the molten pool beneath the arc; this also determines the gas absorption.

It is also shown that the nitrogen content is obviously affected by the electrical polarity. This matter is discussed elsewhere in this paper.

Effect of Wind. The self-shielded arc welding process is usually stable against wind disturbances, although it has not been reported that this process can eliminate any welding problems caused by air currents created by fans or in outdoor applications. According to the extensive research on self-shielded arc welding electrodes with strong deoxidizer CaF₂-CaCO₃ type flux, some effects of wind have been revealed on the fundamental phenomena, including the atmospheric gas absorption, the arc phenomenon, the weld quality, etc.

The effects of air current or wind velocity as reported elsewhere (Ref. 6) were that the nitrogen absorption of weld deposits increases proportionally as the wind velocity increases, while the diffusible hydrogen content in the weld beads on mild steel plate decreases with increasing wind velocity. This trend is more clearly defined for the head wind compared with the tail wind. From Ref. 6 it can be concluded that the atmospheric gas absorption of deposits is almost independent of wind velocity except for the finer droplets under 35 mesh, whose nitrogen content decreases slightly as the wind velocity increases.

Effect of Electrical Polarity. The atmospheric gas absorption of the electrode metal is greatly affected by the electrical polarity (Refs. 10, 11). As shown in Fig. 10, nitrogen absorption in metal droplets is greatest for dcp, followed by dcrp. This extremely high nitrogen content in dcp is probably due to the fact that the nitrogen ions, or the chemically active nitrogen atoms produced by electrical dissociation of molecular nitrogen in the arc, tend to be easily absorbed by the cathode (Ref. 10), i.e., the electrode. In Fig. 10, a close relationship could not be established between the nitrogen content and the welding current for any of the polarities. As illustrated in Fig. 11, the atmospheric gas content in the weld deposits is increased in the order of dcrp, dcp and ac.

Comparing Figs. 10 and 11, it can be observed that there is a distinct difference in the nitrogen absorption by the metal droplets and that by weld deposits in dcp and ac welding. This difference must be caused by the differences in the slag covering on the weld deposits in dcp and ac welding. Therefore, the effect of polarity on the nitrogen absorbing phenomenon will be more marked in the case of metal droplets with little slag covering.

Figure 12 shows the distribution of nitrogen, oxygen and other chemical compositions, analyzed diametrically over the cross-sections of metal droplets for each polarity by means of X-ray micro-analysis (X.M.A.). In Fig. 12, particular attention should be paid to the fact that the distribution of the chemical composition including nitrogen was ideal over the complete cross-section of the droplets for all polarities; this occurred even when the X-ray analysis was conducted on the comparatively large droplets, where greater segregation of the composition can be anticipated, compared with the smaller one.

Slight discrepancies can be observed in the case of oxygen and Al, which exhibit minor variations in their X.M.A. curves. These variations perhaps indicate an aluminum oxide, judging from a good correlation between the oxygen and Al variation in the X.M.A. charts. According to this analysis, it can be concluded metallurgically that some elements added to the flux core are homogeneously alloyed during the growth of the metal droplet at the end of the wire and during transfer across the arc gap.

Research on Commercial Electrodes

Fundamental Research for Developing and Improving Commercial Electrodes

In Japan, electrodes with strong deoxidizers of the CaF₂-CaCO₃ type are now widely used in arc or dc self-shielded welding, especially in open field applications (Ref. 1). However, in their initial development, they had many difficulties, such as lack of impact toughness, poor usability, heavy welding fumes, poor electrode feeding and so forth, which precluded their more widespread application. Recently, the authors succeeded in solving these difficulties after many years of research.

Reduction of Al Content. An ob-
vicious degasifier of this type electrode is Al, which greatly affects impact toughness and the radiographic quality of the welds. In ac welding utilizing the arc voltage controlled electrode feeding system, welders had to use a long arc length in order to prevent the electrode from sticking in short-circuiting arc welding, while long arc welding was apt to invite a poor X-ray quality caused by blow hole formation. Therefore, in order to solve this problem in the ac welding system, more Al is added to the flux, resulting in poor impact toughness.

After a long period of research, it was concluded that the Al content in the self-shielded electrode could be substantially reduced by using the dc power source without causing the difficulties described above. From the usable arc voltage range, the impact energy absorbed at 0°C by weld deposits and the Al content as reported in Ref. 12, it may be concluded that, due to the optimum arc voltage range being broadened by the constant potential dc power source, it is possible to use the low Al content electrode for outdoor applications without any problems.

With regard to the impact toughness, the energy level in ac welding is somewhat better than in dc welding with high Al contents, while dc is better than ac with low Al contents. In addition, dc welding is more stable than ac with regard to gas pocket formation. These phenomena are probably a result of differences in the Al consumption with dc and ac welding. In conclusion, dc welding should be recommended for use in the more important applications where a higher degree of X-ray quality and excellent toughness are prerequisites.

**Reduction of Electrode Diameter.**
Reduction of electrode diameter was included in the research program with the aim of improving both the usability in positional welding and the portability of the electrode feeder for semi-automatic welding process. Although the first trial with a reduced electrode size had been made in ac welding the expected results were not obtained. However, in dc welding with a constant potential dc power supply, the desired objective end was attained. This success with the dc system realized many technical advantages for the self-shielded welding process. The improvement of welding efficiency, weight reduction of electrode feeder, improvement of usability and weld quality in positional welding, etc. are all merits of smaller electrode diameter.

As shown in Fig. 13, the impact energies of the weld deposits absorbed at the low temperature of −20°C are markedly affected by the electrode size with a proportionally greater improvement with the smaller electrode sizes. In this case, the electrical polarity also has a distinct effect on the impact toughness — that is, the dcrp weld deposit has superior toughness values while dcs of weld deposit has inferior values.

Electrode size apparently has no effect on the tensile strength of the weld deposits, but does have some effect on the elongation. Contrary to impact toughness, the elongation is improved gradually as electrode size is increased. Moreover, the effect of polarity on the tensile properties is not as clearly defined as with impact toughness (Ref. 5).

**Reduction of Welding Fumes.**
The general application of this process has been limited to both outdoor and indoor use where ventilation is good because of the voluminous welding fumes. Accordingly, a reduction in the welding fumes is one of the important objectives in eliminating these limitations and in extending the present applications.

Judging from Fig. 14 which outlines the relationship between the amount of fumes produced and percentage of the flux ingredients added to the flux core, the ingredient which produces the most fumes must be metallic Mg followed by metallic Al while the role of other minerals in the fume formation is not clear. According to a technical reference covering the physical properties of different materials, high fume producing ingredients may be presumed to be the light metals which have a greater

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**Fig. 10** — Effect of electrical polarity on nitrogen absorption of metal droplets (Ref. 7)

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**Fig. 11** — Effect of electrical polarity on nitrogen and oxygen absorption of self-shielded weld deposits (300 A welding current) 26 V arc voltage; 35 mm electrode stickout; 2.0 mm electrode diameter (Ref. 7)
chemical affinity for oxygen, a lower boiling point and a higher vapor pressure.

In arc welding, these metals are easily vaporized by the great heat of the arc and oxidized at elevated temperature to form a dense shield of their oxide particles, i.e., welding fumes. Mg and Al may be grouped with these metals. So far as the minerals are concerned, such volatile ones as metallic fluorides may produce more fumes in a similar manner to volatile metals as explained above. However, they are less effective than other volatile metals such as Mg and Al in the amount of fume produced.

The authors recently developed a new type of wire (N-55S) to be used in combination with a dc power supply. The relative amounts of welding fume from two kinds of wire (N-55S for dc and N-54 for high toughness ac welding) are clearly shown in Fig. 15. As shown in Fig. 16, the effect of reducing the fume content in N-55S does not prevent high impact toughness in the weld metal.

Surface Treatment of Electrode. A flux cored electrode, especially with a complex cross-section, is inevitably more difficult to feed than solid electrodes. In addition, surface rust has sometimes troubled users of flux cored electrodes in Japan where the weather tends to be more humid in summer. It is also considered that these difficulties have been a great barrier to the wider application of this type electrode.

Accordingly, a series of research experiments concerning wire electrode surface treatment has been conducted to overcome these difficulties. From the results, the authors concluded that the best way to solve such difficulties should be to coat the wire surface with an oily lubricant mixed with powdered lubricants. In this process, any hydrogen sources should be eliminated from the lubricant ingredients since the hydrogen will become more active in a strongly deoxidized molten metal such as that from the self-shielded arc welding electrode of the strong deoxidizer CaF₂-CaCO₃ type which could then give rise to cracking and porosity formation in the welds.

Some oscillograms were made of the armature current change of the electrode feeding motor during feeding two test electrodes, i.e., with and without surface treatment with the new lubricant. In this test, the conduit without any supply of powdered lubricant such as MoS₂, commonly used for welding operations, was coiled to a small diameter of 400 mm in order to make the test more stringent.

The oscillograms indicated that the surface treatment permits smoother feeding with lower armature current, while in the case of untreated electrodes, feeding is sometimes interrupted with unsteady higher armature current.

It has also been found that the treated electrode has excellent resistance to rust formation even when it has been exposed to the air for a long period. In addition, this treatment has another advantage in which the

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![Fig. 12 — Distribution of nitrogen, oxygen and other chemical compositions in metal droplets, analyzed by X-ray microanalyzer (Ref. 7)](image-url)
treated electrode does not produce more diffusible hydrogen than an untreated one even after exposure to the air for 16 days.

**Industrial Applications of Commercial Electrodes**

**Indoor Applications**

When used for applications such as those shown in Fig. 17, this process can greatly increase efficiency in indoor welding where manual arc welding had previously been employed. In this case, the N-55S electrode which produces less fume is preferred.

**Outdoor Applications**

Outdoor Applications in Civil Engineering and Building Construction. This process is also characterized by its excellent applicability to outdoor welding work, such as civil engineering and architectural building constructions, where auxiliary gas shielded and submerged arc welding processes are less favored by welders because of their comparatively troublesome operation.

For the purpose of establishing the applicability of this process to an architectural building construction, the authors have constructed model test joints approximating the 50 kg/mm² HT steel column to column and column to beam joints on a building construction site. In this test, another commercial electrode (N-55A) for dc welding has assured sound welds with an impact value of about 7 kg-m at 0°C. The process was used for the field application of N-55A on a building construction site, and has also been applied to off-shore constructions.

Outdoor Application in Shipbuilding. The process has been used to apply a high toughness electrode (N-55) to the upper deck structures of an ore carrier on the building berth; the electrode can guarantee an impact value of more than 10 kg-m at 0°C in this application.

**Conclusion**

The study described in this paper has clarified the welding phenomena characterized in self-shielded arc welding and provided useful information for improving commercial flux cored electrodes. The flux cored electrodes recently improved through a long period of research will be utilized in two ways.

One of these is an ac welding system which will be readily adopted from the economical point of view—that is, with respect to low investment in welding equipment. However, with regard to the welding equipment with arc voltage controlling system employed in ac welding, light gauge steel and positional welding will be difficult, even though a small size electrode is used.
The other is a dc welding system, in which atmospheric gas content can be decreased to such a low level that the Al content in the electrode can be minimized. The arc length self-controlling characteristics of the constant potential dc power source is also beneficial in stabilizing the arc, even at a low current in positional welding compared with the ac power source. In addition, the weld metal quality in dc welding is generally better than that in dc welding.

Although self-shielded arc welding was originated with the ac welding system in this country, future progress of this process on the basis of the above merits will be concerned with the fine wire dc welding system rather than with the large size electrode ac welding.

References

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