Coalescence Behavior of Aluminum Alloy Drops in Molten Salts

Raja R. Roy and Yogeshwar Sahai

Department of Materials Science and Engineering, The Ohio State University, Columbus, OH 43210, USA

The coalescence of aluminum and aluminum alloy drops in molten salt flux was observed in different salt fluxes as a function of time. Salts based on equimolar NaCl-KCl with addition of other metal chlorides or metal fluorides were used. All salts showed the ability to coalesce metal drops into one drop, but time taken for complete coalescence was different for different salts. Metal drops are covered with oxide film, which hinders their ability to coalesce into one metal drop. Thus, the coalescence ability of any salt depends on the efficiency of oxide removal by the salt. Removal of oxide layer from aluminum surface by equimolar NaCl-KCl and equimolar NaCl-KCl containing 5 mass%NaF was observed by interference microscopy. It was found that the oxide layer was not removed by equimolar NaCl-KCl, while it was removed by equimolar NaCl-KCl containing 5 mass%NaF. Coalescence ability of salt is related to weight loss of metal in salt and interfacial tension between metal and salt.

(Received July 7, 1997)

Keywords: *aluminum remelting, recycling, metal/salt interactions, used beverage can (UBC), interference microscopy, oxide film, molten salt, molten metal coalescence*

I. Introduction

Coalescence ability of any salt is a very important factor in determining its suitability for use as flux in recycling of aluminum scrap. Better coalescence of metal drops in molten salt results in better yield of the process. Coalescence of metal drops results in an increase in the resulting drop diameter, which increases the probability of its separation from the salt flux. On the other hand, a smaller drop is more likely to be entrapped in the salt flux. Coalescence of metal drops is prohibited by the oxide film covering the metal surface. The choice of a salt flux depends on its ability to free the molten aluminum alloy from the oxide film covering.

Oxide layer on aluminum is transparent, and so it can not be observed by ordinary microscope⁽¹⁾. However, stripping of oxide layer can be studied using interference microscopy. A partially detached oxide film can be seen by means of interference fringes developed by the gap between the oxide and metal.

In this study, the coalescence ability of molten salts based on equimolar NaCl-KCl was determined for aluminum drops as well as UBC (Used Beverage Container) alloy drops. Two types of aluminum alloys are used to make beverage cans. The top of a beverage can is made of alloy AA5182, and body of the can is made of alloy AA3004. Body of the can comprises 75% of the weight of a can. UBC alloy, used in this study, was prepared by ALCOA, and its composition corresponded to weighted average of the composition of the aluminum alloys AA5182 and AA3004. The composition of the UBC alloy used in this study was 1.91% Mg, 0.79% Mn, 0.16% Si, and 0.35% Fe. In this work, the progress of coalescence

in different molten salts was observed as a function of time. Coalescence is related to the removal of oxide layer from metal by salts. Interference microscopy was used to study the removal of oxide layer on metal in equimolar NaCl-KCl and equimolar NaCl-KCl containing 5 mass%NaF molten salts. Metal loss of UBC alloy in different salts was measured and was related to the coalescence ability of salts.

II. Experimental

Figure 1 illustrates the test for coalescence of metal drops in salts. Salts were dried in a furnace for 24 h at 723 K. Salt of desired composition was melted in a quartz crucible with round bottom to ensure that the metal chips were in contact inside the molten salt. Following salts were used: equimolar NaCl-KCl and equimolar NaCl-KCl containing 5 mass% of MX, where MX was one of the following salts: LiCl, CaCl₂, MgCl₂, NaF, KF, LiF, MgF₂, CaF₂, Na₃AlF₆, or AlF₃. 100 chips of aluminum or UBC alloy weighing about 2 g were charged in 20 g of molten salt. Salts containing the charge were frozen after specific time intervals, which was varied between one minute to several hours. Salts were rinsed, and coalescence behavior of aluminum drops was analyzed by counting the number of drops resulting after the melting and coalescence.

The study of oxide removal from Al by salts was done using the interference microscopy. A "Carl Zeiss" interference microscope was used for examining the interference patterns. Interference microscope utilizes interference phenomena of light for observation of surface profile. Aluminum sample was cut and ground to 120 grit followed by grinding at 240, 320, 400, and 600 grit.

Fig. 1 Test for coalescence of metal drops in salts.

Then, the sample was electropolished in a mixture of perchloric acid and ethanol as an electrolyte. The beaker with the electrolyte was kept in an ice bath, where the electrolyte temperature was maintained below 298 K. Temperature was continuously monitored while $50 \times 10^{-6} \text{ m}^3$ perchloric acid was slowly added to the $250 \times 10^{-6} \text{ m}^3$ of ethanol. Electrolyte was stirred by a magnet during electropolishing. An Al sample polished to 600 grit was used as anode and a steel sheet was used as cathode. Electropolishing was done at 10 V. The electropolished Al sample was then oxidized in a furnace at 773 K for 15 h. Interference pattern from the electropolished and oxidized Al sample was observed. Subsequently, Al samples were immersed in equimolar NaCl-KCl for 1.5 min and in equimolar NaCl-KCl containing 5 mass% NaF for 0.5 min, 1.5 min, and 2.5 min. The salt temperature was maintained at 1013 K. After immersion in salt, samples were washed in hot water. Interference pattern was observed on the sample surface without any further surface preparation, and photographs were taken.

The weight loss of metal in molten salt was measured as follows. Salts were dried in a furnace for 24 h at 723 K, and 30 g salt mixture of desired composition was melted in an alumina crucible. Weighed UBC alloy samples were charged in the molten salt at 1013 K. After 6 h, salts containing the charge were frozen. Salts were rinsed, and UBC alloy drops were recovered. UBC alloy drops were weighed subsequently on an electronic balance. The difference in weight of UBC alloy before and after the experiment gave the metal loss in the salt.

III. Results

1. Coalescence of aluminum chips

Coalescence of aluminum chips in salts, based on the equimolar NaCl-KCl composition, was observed as a function of time to evaluate the coalescence ability of different salts mentioned in the previous section. All salts showed the ability to coalesce aluminum drops into one single melt pool. Figure 2 shows the aluminum chips be-

Fig. 2 Aluminum chips before the experiment.

After 1 Minute After 2 Minutes

Fig. 3 Coalescence of aluminum drops in NaCl-KCl-5 mass% NaF salt.

fore they were charged in molten salt. Figure 3 shows the progress of coalescence after 1 and 2 min in equimolar NaCl-KCl with 5 mass% NaF salt. Similar results were obtained for all other fluoride additions. Figure 4 shows the progress of coalescence in equimolar NaCl-KCl as a function of time, and it is obvious that it took much longer time for all drops to coalesce into one metal pool without fluoride addition to NaCl-KCl salt. Similar results were obtained for the addition of 5 mass% of LiCl, CaCl_2 , or MgCl_2 in equimolar NaCl-KCl. Figure 5 shows the number of drops remaining as a function of time for salts consisting of these chlorides. Addition of 5 mass% magnesium chloride, calcium chloride, or lithium chloride increased the coalescence time.

The end result of melting the metal chips is the formation of a single drop of metal in all salts. However, the time taken for the formation of a single drop of metal is significantly different for different salts. Aluminum drops coalesced in salts containing fluorides as well as chlorides, however the behavior of salts consisting of chlorides only was significantly different from the salts containing fluorides. A single pool of aluminum formed in less than 2 min for all salts containing fluorides with the exception of MgF_2 , which took about 3 min to form a

Fig. 4 Coalescence of aluminum drops in equimolar NaCl-KCl salt.

Fig. 5 Progress of coalescence with time in equimolar NaCl-KCl with addition of chlorides.

single pool of aluminum. Coalescence in salts consisting of chlorides only took significantly longer time compared to salts containing fluorides. A single pool of aluminum formed in equimolar NaCl-KCl in about 12 h.

It can be seen from Fig. 3 and from experiments with other fluoride additions that the chips join before they have melted completely in salts containing fluorides, while in salts consisting of chlorides only, chips form individual drops before (see Fig. 4) joining together to form a larger drop. The number of drops decreased as the drops coalesced and increased in size. In salts consisting of chlorides only, the coalescence of metal drops was very slow. Partial coalescence of two metal drops can be seen in Fig. 4. The reason for the poor coalescence ability of salts consisting of chlorides only was their inability to strip the oxide layer covering the metal.

2. Coalescence of UBC alloy chips

Progress of coalescence of UBC alloy chips was also observed as a function of time in salts based on equimolar NaCl-KCl described in the experimental section. The results of the coalescence studies are shown in Figs. 6-9. Figures 6, 7, and 8 show the progress of coalescence in equimolar NaCl-KCl with 5 mass%NaF, CaF_2 , or AlF_3 addition, respectively. Figure 9 shows remaining drops after different times in NaCl-KCl salt. Similar results were obtained for addition of KF, LiF, or Na_3AlF_6 . Figure 10 shows a plot of the number of drops remaining as a function of time in equimolar NaCl-KCl and Figs. 11 and 12 in NaCl-KCl salt with one of the various fluorides addi-

Fig. 6 Coalescence of UBC drops in NaCl-KCl-5 mass%NaF salt.

Fig. 7 Coalescence of UBC drops in NaCl-KCl-5 mass% CaF_2 salt.

Fig. 8 Coalescence of UBC drops in NaCl-KCl-5 mass% AlF₃ salt.

After 72 Hours After 96 Hours

Fig. 9 Coalescence of UBC drops in equimolar NaCl-KCl salt.

Fig. 10 Progress of coalescence of UBC alloy drops as a function of time in equimolar NaCl-KCl.

Fig. 11 Progress of coalescence of UBC alloy drops as a function of time in equimolar NaCl-KCl with addition of fluorides.

Fig. 12 Progress of coalescence of UBC alloy drops as a function of time in equimolar NaCl-KCl with addition of fluorides (different time scale compared to Fig. 11).

tion. Figures 11 and 12 are for the same salts but plotted on different time scales. Figure 11 clearly shows that the addition of 5 mass% NaF, KF, LiF, or cryolite is very effective in coalescence of metal drops. Figure 13 shows the number of drops remaining as a function of time in equimolar NaCl-KCl containing 5 mass% addition of

Fig. 13 Progress of coalescence of UBC alloy drops as a function of time in equimolar NaCl-KCl with addition of different ratios of NaF to AlF₃.

NaF and AlF₃ in varying molar ratios. As the ratio of NaF/AlF₃ increases, the coalescence ability of the salt also increases.

Coalescence of the UBC alloy drops was more difficult than the coalescence of aluminum drops. The UBC alloy contains magnesium, which makes UBC alloy to oxidize more severely than aluminum. Thus, the UBC alloy is covered with an oxide layer that is much thicker than the oxide layer covering aluminum metal, and therefore, it is more difficult to strip the oxide layer from the UBC alloy compared to aluminum.

The extent of coalescence for UBC alloy chips differed for various fluorides used. Complete or nearly complete coalescence was observed for salts containing NaF, KF, LiF, or Na₃AlF₆ after 2 min, while formation of large number of drops was observed for salts containing MgF₂, CaF₂, or AlF₃. Although coalescence of Al chips was found to be similar for all salts containing fluorides, significant difference was observed for the coalescence of the UBC alloy chips in different salts containing fluorides. The thick oxide layer on the UBC alloy chips is more difficult to strip, and the difference in the coalescence ability of salts containing different fluorides can be seen in these experiments.

The coalescence of UBC alloy chips in equimolar NaCl-KCl took much longer (see Figs. 9 and 10) compared to the coalescence of Al chips in equimolar NaCl-KCl. The UBC chips took a very long time to change their shape to spherical drops. The surface of UBC alloy drops appeared dull and rough because the surface of UBC alloy drops was covered with a thick layer of oxide. Although the UBC alloy drops coalesced as time progressed, the coalescence was extremely slow. The coalescence was not complete even after the UBC alloy chips were immersed in equimolar NaCl-KCl for 96 h. Thus, it can be concluded that salt takes longer time to decrease the strength of oxide layer on UBC alloy than pure Al.

Based on these experiments, salts can be classified in four categories depending on their coalescence ability:

- (1) Excellent: NaCl-KCl with addition of NaF, KF, LiF, or Na₃AlF₆
- (2) Good: NaCl-KCl with addition of CaF₂ or MgF₂
- (3) Moderate: NaCl-KCl with addition of AlF₃
- (4) Poor: NaCl-KCl

3. Observation of oxide removal using interference microscopy

Interference patterns from the Al samples are shown in Figs. 14–18. Figure 14 shows the interference fringe pattern from an oxidized electropolished aluminum sample. The fringe pattern consisted of parallel dark and bright fringes, which is characteristic of a plane surface. When the surface is not plane, then the fringes bend. In this case, if the oxide layer was partly stripped from the surface, the fringes would bend.

Figure 15 shows the interference pattern from an oxidized electropolished sample immersed in equimolar NaCl-KCl for 1.5 min at 1013 K. The fringe pattern consisted of parallel lines, which indicated that removal of oxide layer from Al surface had not taken place. Figure 15 also shows cracks formed in the oxide layer due to thermal stresses that generated between aluminum and oxide layer due to heating.

Fig. 14 Interference pattern from electropolished Al surface oxidized for 15 h at 773 K.

Fig. 15 Interference pattern from electropolished Al surface immersed in equimolar NaCl-KCl for 1.5 min at 1013 K.

Fig. 16 Interference pattern from electropolished Al surface immersed in equimolar NaCl-KCl containing 5 mass%NaF for 0.5 min.

Fig. 17 Interference pattern from electropolished Al surface immersed in equimolar NaCl-KCl containing 5 mass%NaF for 1.5 min.

Fig. 18 Interference pattern from electropolished Al surface immersed in equimolar NaCl-KCl containing 5 mass%NaF for 2.5 min.

The interference fringe pattern from the sample immersed in equimolar NaCl-KCl containing 5 mass%NaF for 0.5 min at 1013 K is shown in Fig. 16. The Al sample was coated with solidified salt, when it was taken out of the salt. When the sample was immersed in the salt, the

salt first solidified around the sample and then, started to melt as temperature of the sample increased. Interference pattern from this sample showed set of parallel lines, which indicated that removal of oxide layer from Al surface had not started. Once the salt melted around Al sample, then oxide layer was stripped from the surface rapidly. This can be seen from the interference patterns from the sample immersed in equimolar NaCl-KCl containing 5 mass%NaF for 1.5 min at 1013 K as seen in Fig. 17. The interference pattern from the sample immersed in equimolar NaCl-KCl containing 5 mass%NaF for 2.5 min showed that stripping of oxide layer was still in progress as seen in Fig. 18. Thus, it can be seen that the removal of oxide layer from Al surface did not take place in equimolar NaCl-KCl, while removal of oxide layer from Al surface in equimolar NaCl-KCl containing 5 mass%NaF was very rapid and part of the oxide layer was removed even before aluminum completely melted. This is in agreement with the observation of progress of coalescence in salts consisting of chlorides and salts containing fluorides.

4. Metal loss

Metal loss of UBC alloy in salt flux is shown in Table 1. Metal loss was the least in equimolar NaCl-KCl and increased with the addition of fluorides. The coalescence abilities of the salts are also listed in Table 1. Metal loss in salts correlates well with their coalescence abilities. The salts containing NaF, KF, or LiF showed excellent coalescence ability, and the metal loss was the most in these salts. Equimolar NaCl-KCl showed poor coalescence ability, and the metal loss was the least in this salt. The salts containing AlF_3 , MgF_2 , or CaF_2 showed moderate or good coalescence abilities, and the metal loss was intermediate in these salts.

IV. Discussion

An aluminum alloy piece at room temperature is covered with a thin layer of oxide. This oxide layer is compact and strong prior to being charged in salt. As the temperature of the oxide layered metal increases, cracks may develop in the oxide layer due to the difference in their coefficients of thermal expansion. When the metal inside the oxide layer melts, it tries to assume its equilibrium

Table 1 Metal loss and coalescence of UBC alloy drops.

Salt	Metal loss (g)	Coalescence
Equimolar NaCl-KCl	0.002	Poor
Equimolar NaCl-KCl + 5 mass%MgF ₂	0.010	Good
Equimolar NaCl-KCl + 5 mass%CaF ₂	0.009	Good
Equimolar NaCl-KCl + 5 mass%AlF ₃	0.014	Moderate
Equimolar NaCl-KCl + 5 mass%NaF	0.071	Excellent
Equimolar NaCl-KCl + 5 mass%KF	0.028	Excellent
Equimolar NaCl-KCl + 5 mass%LiF	0.045	Excellent

shape of a sphere. However, oxide layer tries to restrict this deformation. Once the oxide layer is weakened by the attack of salt and is no longer compact, metal can deform to spherical shape even though the oxide layer is attached to it at several places.

The process of oxide removal of aluminum alloy drops can be understood by the mechanism proposed by Jordan and Milner⁽¹⁾. When aluminum alloy covered with thin layer of oxide is charged in molten salt, oxide layer is stripped by a three-step process which is schematically shown in Fig. 19.

- (1) Openings develop in oxide layer.
- (2) Salt penetrates between oxide and metal.
- (3) Oxide layer is stripped.

There are three important time intervals governing the progress of coalescence.

- (1) Time for melting of a metal piece (t_m).
- (2) Time for weakening of strength of oxide layer (t_w).
- (3) Time for stripping of significant fraction of oxide layer (t_s).

Progress of coalescence of aluminum and UBC alloy chips in different salts can be illustrated by the relative values of these three-time intervals.

1. Coalescence of aluminum drops in salts containing fluorides

In these cases, coalescence of drops is very fast. Progress of coalescence is illustrated by Fig. 20 in these cases. Aluminum chips join together before the chips have melted completely. Thus in this case, the oxide layer has weakened and a significant fraction of the oxide layer

Fig. 19 Schematic representation of oxide removal and coalescence process.

Fig. 20 Schematic representation of oxide removal and coalescence process in salts where coalescence is very fast.

has been stripped even before chips have melted completely. The oxide layer has weakened due to increase in volume of aluminum upon heating. As the openings develop in oxide layer, the aluminum starts dissolving in the salt undermining the oxide layer. The oxide layer then curls up from the surface of aluminum due to thermal stresses. The following relation holds between the three time intervals

$$t_w, t_s < t_m. \quad (1)$$

2. Coalescence of aluminum drops in chlorides

In this case coalescence of drops is very slow. Chips melt completely and form metal drops and then these drops keep coalescing as time progresses. Progress of the coalescence is illustrated by Fig. 21 for this case. Oxide layer is not stripped to a significant extent in this case, but cracks develop due to thermal stresses. When drops come in touch, drops start coalescing with metal inside the oxide layer joining along the cracks. Coalescence is favored by decrease in free energy due to reduction in surface area. Thus, melting of metal chips is faster than stripping of oxide layer and

$$t_m, t_w < t_s. \quad (2)$$

3. Coalescence of UBC alloy drops in salts containing fluorides

Coalescence of UBC alloy drops in salts containing 5 mass% of NaF, KF, LiF, and Na_3AlF_6 was found to be very fast and therefore $t_w, t_s < t_m$ for these salts. Process of coalescence proceeds as in Fig. 20. For salts containing MgF_2 , CaF_2 , or AlF_3 , multiple drops formed, which

Fig. 21 Schematic representation of oxide removal and coalescence process in salts where coalescence is slow.

coalesced slowly with the progress of time. Process of coalescence proceeds as in Fig. 22 and in this case also,

$$t_m, t_w < t_s. \quad (2)$$

4. Coalescence of UBC alloy drops in chlorides

From Fig. 9, it is clear that UBC alloy chips could not deform to spherical shape even after being immersed in molten salts for many hours. The reason for this behavior is that molten metal inside is being restricted from assuming a spherical shape by a tenacious oxide layer. Thus time for weakening of strength of oxide layer is large in this case. Process of coalescence proceeds as in Fig. 21. For coalescence of the UBC alloy drops in equimolar NaCl-KCl,

$$t_m < t_w < t_s. \quad (3)$$

It is a well known fact that the addition of fluorides in NaCl-KCl increases the coalescence ability of salt, but the reason for this behavior is not very well understood. Peterson⁽²⁾ has suggested that solubility of alumina in salts could be the deciding factor in this regard. West⁽³⁾ measured the solubility of alumina in different fluxes and determined that alumina was virtually insoluble in fluxes. In a work conducted at ALCOA Research Laboratories, alumina windows, produced by stripping away the metal substrate from anodized aluminum samples, were immersed in molten flux⁽⁴⁾. No thinning of oxide windows was reported. Thus, there remains little doubt that salt fluxes do not dissolve oxide to any appreciable extent, and it is unlikely that solubility of alumina in salt flux determines the coalescence ability of salt flux. West⁽³⁾ proposed that the oxide layer was detached by the forma-

Fig. 22 Schematic representation of oxide removal and coalescence process in salts containing MgF_2 , CaF_2 , AlF_3 .

tion of volatile aluminum chloride at the oxide metal interface. However, this explanation is not plausible, because salts consisting of chlorides only are not very efficient in stripping the oxide layer from metal. Also, reaction of aluminum with chlorides is unlikely from the free energy consideration.

Sully *et al.*⁽⁵⁾ gave an alternative criterion based on the interfacial tension characteristics. According to them, oxide layer was detached from metal, when the following criterion was satisfied

$$\gamma_{\text{metal/flux}} + \gamma_{\text{oxide/flux}} < \gamma_{\text{metal/oxide}} \quad (4)$$

which is equivalent to saying that the change in free energy due to the detachment of oxide from metal, i.e. the work of adhesion between metal and oxide, should be negative. The change in free energy due to oxide film removal is given by eq. (5).

$$\Delta G = S(\gamma_{\text{metal/flux}} + \gamma_{\text{oxide/flux}} - \gamma_{\text{metal/oxide}}) \quad (5)$$

when ΔG is negative, eq. (5) is satisfied. However, measurements of interfacial tension and contact angle have shown that the change in free energy due to oxide film removal is positive for salt fluxes, and eq. (5) is not satisfied by any of the salt fluxes⁽⁶⁾.

Jordan and Milner⁽¹⁾ proposed another mechanism for the detachment of oxide from metal by salt fluxes. According to their explanation, the detachment of oxide from metal is electrochemical in nature with the aluminum acting as an anode, the oxide acting as a cathode and salt flux acting as an electrolyte. Aluminum goes into the solution as Al^{3+} ions undermining the oxide film and salt penetrates between aluminum and oxide. Storchai⁽⁷⁾ has also proposed that detachment of oxide film from metal by fluxes is of electrochemical nature.

When aluminum is charged in salt, metal loss takes

place due to displacement reactions and due to dissolution of aluminum in salt. The variation of interfacial tension between aluminum and salt flux with salt composition is related to displacement reactions, and has been described in a previous publication⁽⁸⁾. The coalescence ability of salts matches well with the interfacial tension between aluminum and salt. Addition of NaF or KF in equimolar NaCl-KCl decreases the interfacial tension the most, and these salts are found to have excellent coalescence ability. Addition of CaF₂ or MgF₂ decreases interfacial tension to a lesser degree compared to addition of NaF or KF, and the coalescence ability also decreases. Addition of AlF₃ decreases the interfacial tension the least, and the coalescence ability of this salt is also the poorest among all the fluoride addition. Coalescence ability of salts matches well with the metal loss in salt as well. In Table 1, metal loss of UBC alloy in different salts is presented. It can be seen that any increase in metal loss results in better coalescence ability. This is not surprising, since metal loss is related to interfacial tension due to displacement reactions.

V. Summary and Conclusions

- (1) Salts can be classified in four categories depending on their coalescence ability:
 - (i) Excellent: NaCl-KCl with addition of NaF, KF, LiF or Na₃AlF₆
 - (ii) Good: NaCl-KCl with addition of CaF₂ or MgF₂
 - (iii) Moderate: NaCl-KCl with addition of AlF₃
 - (iv) Poor: NaCl-KCl
- (2) Oxide layer is stripped by a three-step process:
 - (i) Openings develop in oxide layer

- (ii) Salt penetrates between oxide and metal
- (iii) Oxide layer is stripped.

(3) There are three important time intervals determining the progress of coalescence: time for melting of metal chip, time for weakening of strength of oxide layer, and time for stripping of significant fraction of oxide layer.

(4) Oxide layer is stripped by salts containing fluorides, while it is very difficult to strip the oxide layer by salts containing chlorides only.

(5) Coalescence ability of salts is related to the metal loss in salt and interfacial tension between metal and salt flux.

Acknowledgment

The financial support provided by Bureau of Mines through the Generic Mineral Technology Center for Pyrometallurgy is gratefully acknowledged.

REFERENCES

- (1) M. F. Jordan and D. R. Milner: *Journal of the Institute of Metals*, **85** (1956-57), 33.
- (2) R. D. Peterson: *Second International Symposium—Recycling of Metals and Engineered Materials*, ed. by J. H. L. Van Linden, D. L. Stewart, Jr. and Y. Sahai, The Minerals, Metals & Materials Society, (1990), p. 69.
- (3) E. G. West: *Trans. Inst. Weld.*, **4** (1941), 50.
- (4) J. R. Terril, C. N. Cochran, J. J. Stokes and W. E. Haupin: *Welding Journal*, (1971), p. 833.
- (5) A. H. Sully, H. K. Hardy and T. J. Heals: *Journal of the Institute of Metals*, **82** (1953-54), 49.
- (6) Raja R. Roy and Y. Sahai: *Mater. Trans., JIM*, **38** (1997), 571.
- (7) E. I. Storchai: *Avt. Svarka*, **1** (1975), 36.
- (8) Raja R. Roy and Y. Sahai: *Interfacial Tension in Molten Aluminum Alloys and Salt Systems*, ed. by S. K. Das, Light Metals, The Minerals, Metals & Materials Society Publication, (1993), p. 1067.