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The effects of geometrical and process variables on the quality of cast-on-strap joints

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Abstract

An automated laboratory-scale, cast-on-strap joining process for lead/acid batteries has been developed. This allows tight control of relevant casting parameters such as strap mould and metal temperature, lug immersion speed, and the time between strap filling and lug entry into the molten strap. The joining of lead–antimony or lead–tin strap alloys with lead–antimony or lead–calcium–tin lugs is studied. It is found that lead–tin is not suitable as a strap alloy for the alloy combinations and joining conditions that have been investigated. Penetration depth of the lug into the strap is found to be critical and may be optimized for a given lug thickness under fixed process conditions. The joint quality improves with a deeper penetration of the thicker lugs for the geometrical configurations studied in this work. It is far easier to form a sound joint with thin lugs as these are not as sensitive as thick lugs to variations in the joining conditions.

Keywords: Lead/acid batteries; Grid alloys; Cast-on-strap; Lead; Tin; Antimony

1. Introduction

The cast-on-strap (COS) process is used in lead/acid battery manufacture to group the individual plates in each cell. As the weight of the cells is supported by these joints, it is important that a strong joint is made.

As noted by Prengaman [1], a study by the BCI Technical Committee on automotive batteries concluded that manufacturing defects were a major cause of failure. Poor lug/strap joining and through-the-partition welding were the major manufacturing defects identified.

Quality control in this area of battery manufacture (COS) is poor as, in practice, the only procedures used are random visual inspection and occasional pulling of plates to determine whether any are loose [2]. These procedures do not measure the degree of fusion, porosity or the meniscus angle, and are highly subjective and subject to operator variation. This type of quality control cannot be used for continuous process improvement, and poor quality joints could routinely pass such inspections. A poor quality joint is characterized by lack of fusion and/or porosity at the lug/strap interface.

Very little has been published in the open literature on the manufacture and properties of COS joints. Previous work at the Pasminco Research Centre (PRC) has focused on the effects of temperature and alloy composition on the nature of COS joints [3,4]. The present study considers variations in the composition of lug and strap alloys, but concentrates more on the role of the geometry of the joint.

This paper discusses the influence on the quality of COS joints of geometrical factors such as lug thickness, penetration depth, and the joining of thick and thin lugs into a common strap. The only process variable studied is the strap-mould temperature.

2. Experimental

2.1. Alloys used

BHAS 99.99% lead was used as the base alloy for the non-commercial strap alloys, whilst commercially-pure tin was used for alloying. The alloys were prepared at 500 °C using a graphite crucible in a top-loading resistance furnace. The alloys used are listed below and their compositions are given in Table 1.

2.1.1. Strap alloys

Pb–3.1wt.%Sb, Pb–2wt.%Sn
Pb–4.25wt.%Sn

2.1.2. Lug alloys

Pb–1.7wt.%Sb, Pb–0.1wt.%Ca–0.3wt.%Sn
Pb–0.1wt.%Ca–1.0wt.%Sn

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Table 1
Composition (wt.%) of lug and strap alloys (balance lead)

Alloy	Sb	As	Cu	Se	S	Ca	Sn	Al	Bi
Very low Sb	1.7	0.23	0.052	0.019	0.0016				0.013
Ca–Sn						0.1	0.29	0.014	0.022
Low Sb	3.09	0.047	0.004	0.018			0.05		0.013

2.1.3. *Lug/strap alloy combinations*

Pb–1.7wt.%Sb/Pb–3.1wt.%Sb
Pb–0.1wt.%Ca–0.3wt.%Sn/Pb–3.1wt.%Sb
Pb–0.1wt.%Ca–0.3wt.%Sn/Pb–2wt.%Sn
Pb–0.1wt.%Ca–0.3wt.%Sn/Pb–4.25wt.%Sn
Pb–0.1wt.%Ca–1.0wt.%Sn/Pb–3.1wt.%Sb

2.2. *Lug casting*

In practice, COS joints are formed via a grid-strap joint. In this study, however, hand-cast lugs are used to form the joint. To investigate the effect of lug thickness, a mild-steel mould was designed to produce 0.9, 1.3 and 1.7 mm thick lugs (11 mm width and 30 mm height). The metal was held at 500 °C. The lug mould was heated to 160 °C for casting as this temperature has been found [4] to produce a microstructure comparable with those of lugs cast on a Wirtz 40C grid caster. The lug mould was periodically corked prior to casting to prevent excessively rapid freezing.

The lug pretreatment step was identical to that described elsewhere [3,4] with the exception of lug polishing. Polishing of the lug to 600 grit was found to have no effect on the quality of the joint for a range of alloys and conditions.

2.3. *Automated cast-on-strap apparatus*

In contrast to previous work at PRC [3,4], joints for this work were produced using a fully automated rig. In the previous work [3], the lugs were hand-dipped and the mould hand-filled and, hence, the reproducibility of experimental conditions could not be guaranteed with this type of operation. The automated rig allowed the control of parameters such as dipping and mould-filling speed, ladle temperature, and the time between mould fill and lug immersion.

A photograph of the rig, with all major features labelled, is shown in Fig. 1(a). A schematic diagram of the strap mould and cavity is shown in Fig. 1(b). Both the ladle and strap mould were heated using cartridge heaters. The temperatures of the latter were controlled by Eurotherm controllers.

Due to heat losses, the ladle was held at 550 °C to deliver metal to the strap mould at approximately 500 °C. To hold this ladle at 550 °C, a composite design was required. The inside of the ladle was made of highly conductive graphite with an outer casing of ceramic as insulation. This design minimized heat losses and enabled rapid heating of the ladle to the desired temperature with a relatively small cartridge heater.

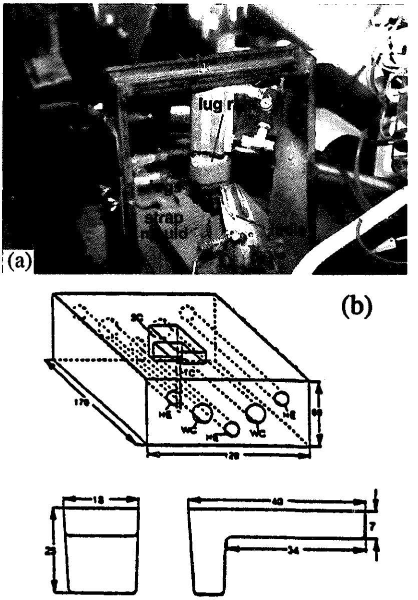

Fig. 1. (a) Close-up of cast-on-strap ring showing ladle and lug ram with lugs attached. (b) Design details of strap mould and dimensions of strap cavity [3]. Unit: mm; SC: scrap cavity; HE: heating element; WC: water cooling and TC: thermocouple.

2.4. *Production of COS joints*

All the apparatus parameters were set prior to the manufacture of joints. The important parameters included: (i) lug immersion and strap-mould filling speeds; (ii) the delay time between strap-mould fill and lug immersion, and (iii) mould and ladle temperature.

The as-cast lugs were wiped clean before placing in the lug holder. The latter allowed setting of both the lug spacing and the lug penetration depth. The depth was measured from the base of the strap cavity. Once fixed in place, the lugs were dipped in commercial flux solution (TBS No. 5 oil-based flux for antimonial lugs; TBS No. 6 acid-based flux for calcium alloy lugs). The excess flux was lightly removed with absorbent paper.

The jig containing the prepared lugs was attached to the pneumatic lug ram (see Fig. 1(a)) ready for manufacture. Molten strap metal at 500 °C was transferred from the holding furnace to the heated ladle. The movement of the ladle and lug ram were actuated by an air switch on the control panel. Once the strap metal had solidified, the strap mould was water cooled to around 150 °C and the completed joint removed.

2.5. *Geometrical and process variables*

A number of the available geometrical and process variables were kept constant throughout the experimental programme. The values of these parameters were determined during initial trials and chosen so as to maximize the quality of the joint produced. Throughout the experimental programme, lug and ladle ram speed, time between lug ram and ladle ram trip and the ladle temperature were all held constant. Only the strap-mould temperature was used as a process variable.

The lug spacing, strap cavity dimensions and lug width were all held constant [3]. Lug thickness (0.9, 1.3 and 1.7 mm) and lug penetration depth (2, 3 and 4 mm from the base of the strap) were the major geometrical variables considered. The joining of lugs of varying thickness into a common strap was also part of the experimental programme.

2.6. *Assessment of joint quality*

Each joint was sectioned, cold mounted in epoxy, and polished to a 1000-grit finish. For antimonial joints, a 10:1 acetic acid:peroxide etchant was used. For joints containing calcium alloy lugs, a more aggressive 3:1 solution was used, irrespective of the strap alloy. The quality of each joint was assessed by metallographic examination.

A macrograph was taken of each joint to highlight any porosity and lack of fusion over the entire joint. These defects are the most important for the assessment of joint quality and, therefore, macrographs were used extensively.

Optical micrographs were used more sparingly, and always in conjunction with the macrograph to highlight points or to reveal local microstructure where relevant. For microstructural examination, the areas of greatest interest were the meniscus and lug tip, although some micrographs of the mid lug region were also taken as appropriate.

3. Results and discussion

3.1. *Effect of strap-alloy composition*

To examine the effect of strap-alloy composition on joint quality, a range of COS joints were prepared using Pb–3.1wt.%Sb, Pb–2wt.%Sn or Pb–4.25wt.%Sn as the strap alloy. In all three cases, Pb–0.1wt.%Ca–0.3wt.%Sn lugs were used. For all the joints discussed in this section, the 0.9 mm thick lugs were immersed to within 2 mm from the base of the strap, and the 1.7 mm lugs to within 4 mm from the base of the strap. Unless stated otherwise, the strap mould was held at 240 °C for the formation of all joints.

3.1.1. *Calcium-alloy lugs with Pb–3.1wt.%Sb and Pb–2wt.%Sn straps*

A macrograph of a joint formed using calcium alloy lugs and an Pb–3.1wt.%Sb alloy strap is shown in Fig. 2(a). It is clear that this joint is virtually free of porosity, and that a slightly positive meniscus is formed about all lugs. A close up of the meniscus region for this joint is seen in Fig. 2(b). It can be seen that there is excellent fusion at the lug/strap interface. A high amount of eutectic is found in the meniscus area; it can be concluded that this was amongst the last metal to freeze in the joint. Fig. 2(c) and (d) shows the lug tip region for thin and thick lugs, respectively. In both cases, excellent fusion has been achieved and results in the formation of a strong bond between the lug and strap.

When Pb–2wt.%Sn is used as the strap alloy, the quality of the joint is greatly reduced, as is evident in the macrograph shown in Fig. 3(a). In this case, significant lack of fusion is seen around the thicker lugs, with excessive melting of the thinner lugs. The joint meniscus is highly negative and, combined with the lack of fusion, a crevice has formed which would retain acid and possibly result in catastrophic failure of the joint. This would result in a joint of very low strength (possibly resulting in lug pull out) and low conductivity.

The crevice at the meniscus is clearly shown in Fig. 3(b). A close-up of the lug tip for a thinner lug which is extensively melted is given in Fig. 3(c). The lack of fusion at the thicker lugs is shown in Fig. 3(d), which is a close-up of the lug tip of one of these lugs.

The explanation for these observed differences may be found by referring to the respective phase diagrams (Pb–Sn, Fig. 4(a); Pb–Sb, Fig. 4(b)). The Pb–Sb diagram is for non-equilibrium cooling [1] and this is the reason for the low-solubility limit of 1 wt.% Sb, rather than the value of 3.5 wt.% given in the equilibrium diagram. A non-equilibrium diagram for Pb–Sn could not be found, but as the solubility is close to 20 wt.%, the movement of the solubility limit through rapid cooling should not affect the discussion of 2 wt.% Sn alloys.

With a 3.1 wt.% Sb alloy, around 20% of the metal will transform to eutectic during cooling. In localized areas (such as the meniscus and lug/strap interface), this proportion will be significantly higher. The eutectic does not solidify until 250 °C and, thereby, will allow time for the flux to fully react and the gaseous reaction products to escape.

With a Pb–Sn strap, there is no formation of eutectic and the material is fully solidified at around 300 °C after moving through a very small temperature range in the two-phase region ($\alpha + L$) of the Pb–Sn phase diagram. Hence, the strap freezes rapidly and the flux does not react fully. Also, as no major structural transformations take place during solidification, the freezing time is further reduced in comparison with joints formed using Pb–Sb straps.

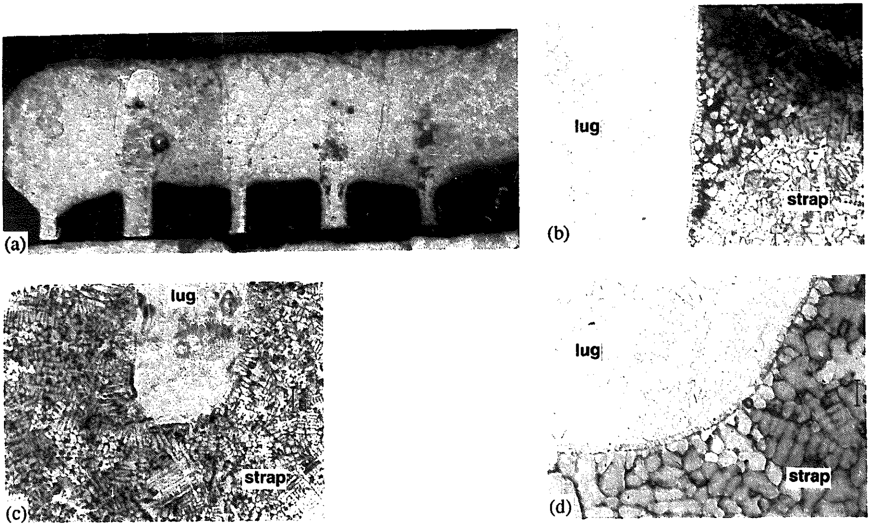

Fig. 2. Calcium alloy lugs with Pb–3.1wt.%Sb strap, giving excellent fusion, low porosity and positive meniscus: (a) macrograph; (b) meniscus area; (c) lug tip (thin), and (d) lug tip (thick).

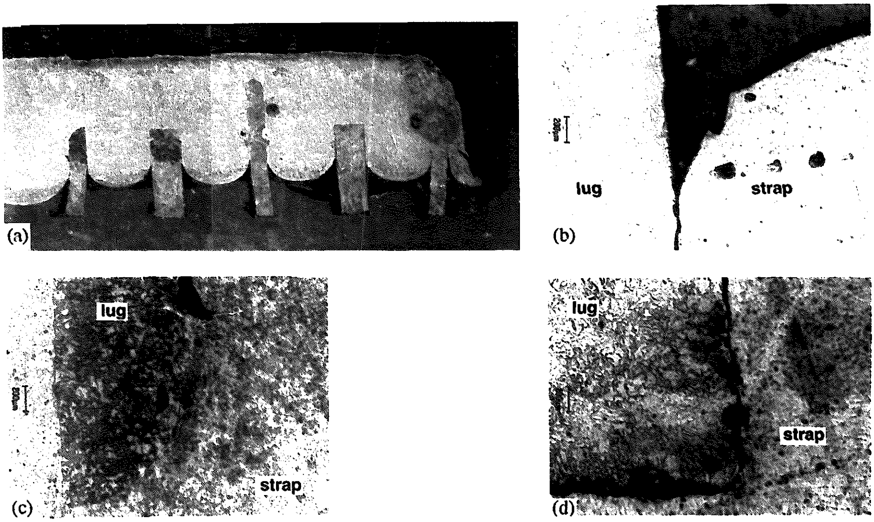

Fig. 3. Calcium alloy lugs with Pb–2wt.%Sn strap, displaying poor fusion at thick lugs, excessive melting of thin lugs and negative meniscus: (a) macrograph; (b) meniscus area, (c) lug tip (thin), and (d) lug tip (thick).

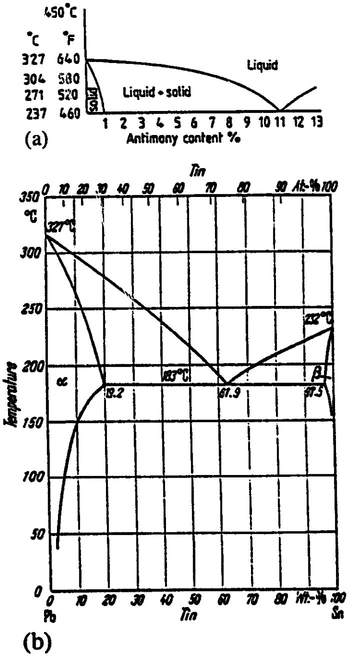

Fig. 4. (a) Pb–Sb non-equilibrium phase diagram [1]. (b) Pb–Sn equilibrium phase diagram.

3.1.2. Increasing tin level in the strap alloy

As the tin level in the strap is increased, it would be expected that the quality of the joint would improve. For a significant improvement in joint quality, however, a substantial amount of tin would be required to lower the melting point and to increase the freezing range. The addition of further tin does present one disadvantage due to the formation of additional precipitates of pure tin that retard the movement of gases to the surface after the reaction of the flux. This can lead to high porosity at, and near, the interface.

Work by Dausmann [4] suggested that a high-quality joint could not be achieved in this system until the tin was increased to at least 4.25 wt.%. A joint formed with a Pb–4.25wt.%Sn strap is shown in Fig. 5 for a strap-mould temperature of 240 °C. The increased amount of tin largely eliminates the problem of lack of fusion, but results in significant melting of the lugs. In the case of the outer thin lugs, this melting is so severe that there is virtually no lug remaining within the strap to act as an anchor. Lug melting of this magnitude can reduce significantly the strength of a COS joint and the highly negative meniscus seen with 2 wt.% tin is still evident.

Fig. 5. Macrograph of joint formed using calcium alloy lugs and Pb–4.25wt.%Sn strap, magnification ×2.5. (Note excessive melting of thinner lugs and negative meniscus.)

3.2. Lug thickness

All joints discussed in this section were made with low-antimony (1.7 wt.%) lug alloy. Similar joints were prepared using calcium alloy lugs, and it was seen that the same general principles applied.

Fig. 6(a) and 7(a) show macrographs of joints produced with 0.9 mm and 1.7 mm lugs, respectively. In each case, the lug tips were 2 mm from the base of the strap. Though some porosity is evident in Fig. 6(a), it is significantly less than in Fig. 7(a). The faster cooling expected in the latter case would reduce the time during which entrained air and gaseous products of the flux reaction can escape from the strap.

Fig. 6(b) shows the meniscus region of the joint formed with the thinner lugs, whilst the corresponding region for a thick lug joint is displayed in Fig. 7(b). There is a greater amount of high eutectic material in Fig. 6(b) and the meniscus angle is less negative than in Fig. 7(b).

Micrographs of the lug tips for thin and thick joints are presented in Figs. 6(c) and 7(c), respectively. The more diffuse nature of the joint made with the thinner lugs is probably due to the reduced volume of solid metal that is available to act as a heat sink. In this case, melting of the lug surface to initiate the joining process would require less heat from the surrounding strap and, hence, the joint would require more time to form.

3.3. Lug penetration depth

Joints made using thick (1.7 mm) low-antimony (1.7 wt.%) lugs will be discussed in this Section. Joints produced with thin lugs (0.9 mm) will not be discussed in detail here as they are not as sensitive to variations in penetration depth. Furthermore, since joints formed using calcium-alloy lugs behaved in the same manner as low-antimony, the following discussion may be applied to lugs of either alloy.

From Fig. 8(a) (lugs 2 mm from strap base) and 9(a) (lugs 4 mm from strap base), it can be seen that the size of pores is reduced by deeper immersion. This observation may be explained through examination of Fig. 8(c) (2 mm from base) and Fig. 9(c) (4 mm from strap base). The highly directional solidification seen with the shallower immersion is indicative of rapid cooling, and the rapid chilling of the strap has resulted in trapping of gas bubbles to give the large

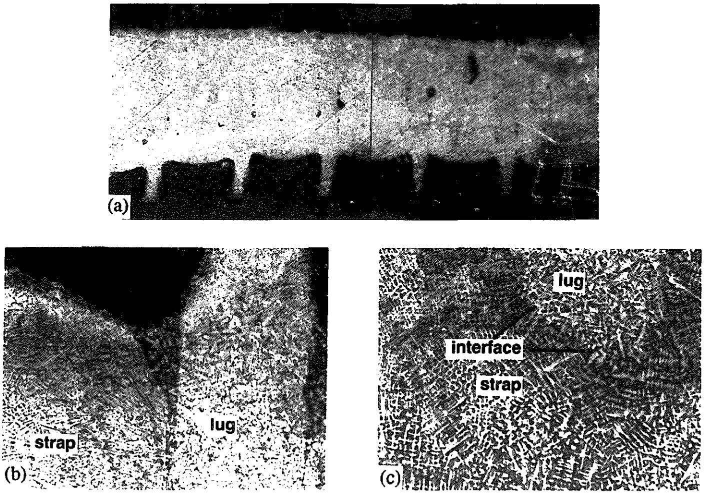

Fig. 6. Microstructure of lug/strap joint using thin, low-antimony lugs and antimonial strap, strap mould at 240 °C: (a) macrograph, magnification ×2.5; (b) meniscus area, magnification ×37.5, and (c) lug tip, magnification ×37.5.

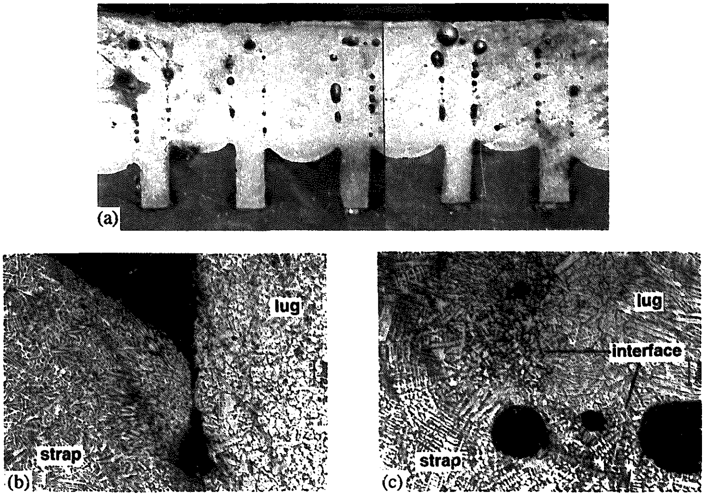

Fig. 7. Microstructure of lug/strap joint using thick, low-antimony lugs and antimonial strap, strap mould at 240 °C: (a) macrograph, magnification ×2.5; (b) meniscus area, magnification ×37.5, and (c) lug tip, magnification ×37.5.

pores observed in Fig. 9(a). With increased depth of penetration, this columnar structure is replaced by a less-directional, dendritic structure and the longer solidification time leads to smaller pores. The meniscus regions for the two cases are shown in Fig. 8(b) (deeper immersion) and Fig. 9(b). Though the effect is not dramatic, there is more eutectic material present and the meniscus angle is less negative with a deeper immersion.

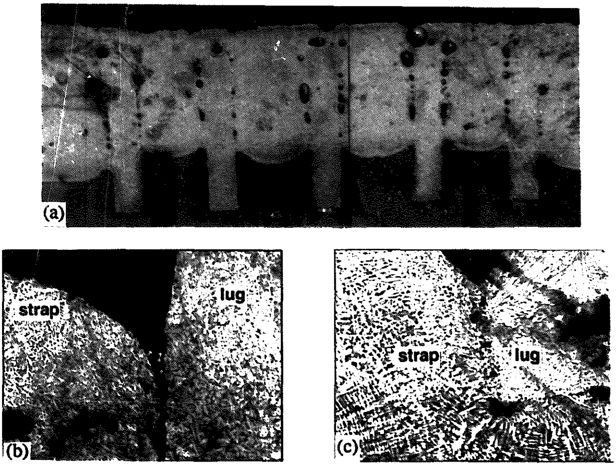

Fig. 8. Microstructure of lug/strap joint formed using thick, low-antimony lugs immersed to 2 mm from the base of the antimonial strap, strap mould at 240 °C: (a) macrograph, magnification ×2.5; (b) meniscus area, magnification ×37.5, and (c) lug tip, magnification ×37.5.

Fig. 9. Microstructure of lug/strap joint formed using thick, low-antimony lugs immersed to 4 mm from the base of the antimonial strap, strap mould at 240 °C: (a) macrograph, magnification ×2.5; (b) meniscus area, magnification ×37.5, and (c) lug tip, magnification ×37.5.

Although the quality of the joint is increased by increasing the depth of immersion, significant porosity is still present. It may be possible that, between the two depths tested, there is an optimum depth that maximizes joint quality. This optimum would depend on lug thickness and the various process parameters such as strap-mould temperature and immersion speed.

It is far easier to form a high-quality joint with a thin lug, as stated previously. A joint of reasonable quality could be formed at most penetration depths, but a slight improvement in joint quality was observed with a reduced penetration depth (4 mm from the base of the strap) for the thin lugs.

3.4. Joint optimization

The joints discussed in this Section were made with Pb–1.7wt.%Sb lugs of varying thicknesses within the one strap, and were optimized by varying the relative depths of the thin and thick lugs within the strap. Fig. 10(a)–(c) illustrates this point.

As can be seen clearly, Fig. 10(c) shows the highest quality joint and Fig. 10(a) the worst. This emphasizes the results on lug penetration depth, and shows that the porosity is largely removed by increasing the penetration depth of the thick lug. A high-fusion, low-porosity joint is formed at the thin lug in all cases. These results agree with those on lug thickness and penetration depth as individual variables. The quality of the joint formed at the thick lug in Fig. 10(c) is, however, better than that in Fig. 8(a).

3.5. The effect of strap-mould temperature

In this experimental program, the strap-mould temperature was routinely varied between 160 and 240 °C. A joint formed using thin (0.9 mm), low-antimony lugs and an antimonial strap alloy with the strap mould at 240 °C is shown in Fig. 11(a). The identical joint formed with the strap mould at 160 °C is shown in Fig. 11(b).

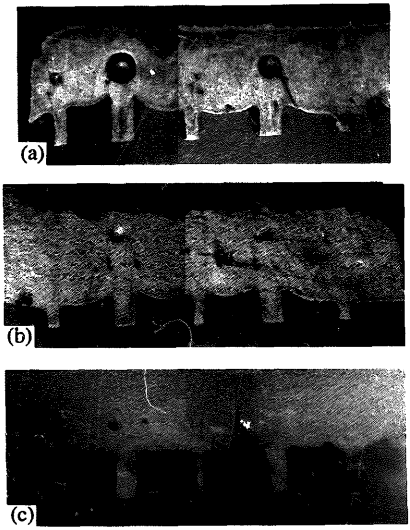

Fig. 10. Macrographs of joints formed using low-antimony lugs and antimonial strap. These show the effect of variations in penetration depth. Strap mould held at 240 °C for all tests. (a) Thick lugs 4 mm from the base of the strap, thin lugs 2 mm from the base of the strap, magnification ×2.5. (b) All lugs 3 mm from the base of the strap, magnification ×2.5. (c) Thick lugs 2 mm from the base of the strap, thin lugs 4 mm from the base of the strap, magnification ×2.5.

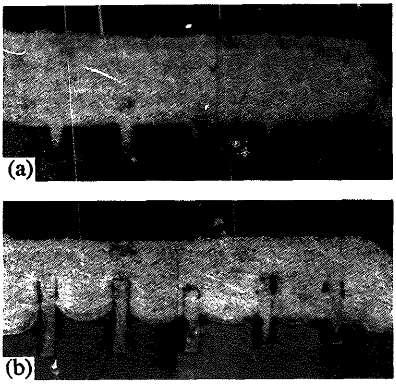

Fig. 11. Macrographs of lug/strap joints formed using thin, low-antimony lugs and antimonial strap alloy. These show the effect of variations in strap-mould holding temperature. (a) Strap mould at 240 °C, magnification ×2.5. (b) Strap mould at 160 °C, magnification ×2.5.

The effect of increasing strap temperature is clear. The porosity is virtually eliminated at the higher temperature. This is due to the increased time available for joint formation and for the escape of the gaseous products of the flux reaction.

4. Conclusions

4.1. Strap-alloy composition

Pb–2wt.%Sn is unsuitable as a strap alloy with calcium alloy (D04) lugs.

Increasing the tin content to 4.25 wt.% in the strap metal increases the degree of fusion. There is, however, excessive melting of lugs when using this strap alloy.

4.2. Lug thickness

Thin (0.9 mm) lugs were easily formed into a sound joint. Thick (1.7 mm) lugs were more difficult to join and the COS joint tended to exhibit a high degree of porosity in the strap near the lug/strap interface.

4.3. Lug penetration depth

Penetration depth was not crucial with thin lugs. A slight improvement in joint integrity was observed with a shallower immersion.

Penetration depth influenced greatly the quality of joints formed with thick lugs. Shallow immersion resulted in the entrapment of large porosity due to localized freezing of the strap metal. Deeper immersion removed this large porosity, but tended to form smaller pores from the products of the flux reaction.

4.4. Joint optimization

It should be possible to determine an optimum penetration depth for a particular lug thickness and set of experimental conditions. For the conditions in this study, the most sound joint was formed with thin lugs 4 mm from the base of the strap, and with thick lugs 2 mm from the base of the strap. This applies to both calcium and low-antimony lugs joined to a Pb–3.1wt.%Sb strap. When the calcium alloy lugs were joined to Pb–Sn straps, a sound joint could not be formed.

4.5. Strap-mould temperature

Strap-mould temperature is crucial as this controls the contact time of the lugs with molten metal. This time must be sufficiently long to allow the escape of gases generated by the reaction of the flux.

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References

[1] R.D. Prengaman, *The Battery Man*, (Sept.) (1989) 16–32.
[2] L.E. Gardiner, *J. Power Sources*, *38* (1992) 197–227.
[3] Z.W. Chen, J.B. See and W.F. Gillian, *J. Power Sources*, *46* (1993) 311–326.
[4] M. Dausmann, *Final Year Thesis*, School of Materials Science and Engineering, University of NSW, Australia, 1994.