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Simulation of the cast-on-strap process in a finite-element model

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Abstract

A decisive factor of the quality of lead/acid batteries, in terms of performance and life time, is the fusion of the plate lugs to the cast-on-strap (COS). The fully automatic COS process is nevertheless complex and the resulting quality of fusion depends on a number of different parameters such as: the strap volume, the number of lugs, the thickness and the insertion depth of the lugs, the combination of strap and lug alloys, and the thermal parameters such as the temperatures of the melt and the strap mould. To further improve the understanding of this important manufacturing process we have used a finite-element analysis to determine the relative influence of some of these parameters on the thermal history and on the resulting quality of fusion. Simulating a technical process such as COS needs simplification and model assumptions and will not be complete without experimental verification. Details of our approach are given and representative results are discussed. It is concluded that COS simulation is a valuable tool for identifying robust process conditions and optimizing product quality.

Keywords: Lead/acid batteries; Production technology; Cast-on-strap process; Finite-element analysis; Process simulation

1. Introduction

The quality of fusion of the plate lugs to the cast strap in lead/acid batteries is a decisive factor of the quality of a battery. The poor quality of joins can be the cause of premature battery failure due to cracking of the lugs or even the straps; it is therefore critical in terms of performance and life time.

The state-of-the-art technical COS process is nevertheless complex and the resulting quality of the lug/strap joints depends on many different parameters. In production practice, the main parameters are: the volume and the design of the strap, the number and the thickness of lugs, the combination of lug and strap alloys, the fluxing and pretinning procedures, the depth of insertion into the strap melt, the delay time between filling the strap cavity and dipping the lugs, and the basic thermal process parameters such as the initial temperature of the melt and the stationary mould temperature.

In parallel with the development of improved COS machines, investigations have been made over the last several years to evaluate the influence of some of these parameters [1–5]. Straps have been cast under regular production conditions or in laboratory-scale operation and the degree of fusion along the lug/strap interface has been used as the evaluation criterion. Questions concerning the influence of the brushing or fluxing procedures can only be answered by doing this kind of work which is time-consuming.

A simplified but useful view of this method of joining is the model that the heat input to the lugs must be sufficient to melt them partially and to get an intermixture of strap melt and lug material before the solidification of the strap volume starts [1]. The heat content of the melt before pouring, the volume ratio of the strap cavity to the inserted lug volume, different heat-transfer processes and the timing of the insertion will determine the thermal history and, finally, the quality of the lug/strap fusion [4,5].

In order to further improve the understanding of the thermal aspects of the COS process we have used a finite-element analysis to simulate the influence of some process parameters and to check their relative importance to the expected product quality. It was the objective of this program to develop a tool which can be used in the future to evaluate fundamental principles of this process as well as to answer basic questions.

2. COS-process simulation

The first and fundamental step was to define a simplified physical model of the complex technical process. A basic simplification of the actual model is the assumption of a homogeneous temperature distribution in the lugs, the melt

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bath and the steel mould at time zero, i.e. after filling the strap cavity and dipping the lugs into the melt bath. In reality, the melt starts cooling during pouring and the temperature distribution at the moment of dipping the lugs is of course inhomogeneous. Insertion of the lugs will affect the actual situation and the lugs will be heated as soon as the tips contact the melt bath surface. Interpreting the results of the simulation in detail and comparing them with experimental data we have to keep in mind the basic simplifications of this specific model approach.

Any computer-aided simulation of a complex technical process should be accompanied by several verification tests. A numerical model will need realistic values of the basic physical constants such as the effective thermal conductivity of the melt which are not available from literature data; they should be measured. Principal differences between the computed results and experimental data will help to optimize the model and may show the necessity to change some assumptions or to include additional features.

We decided to train our model with simplified laboratory-scale experiments. Fig. 1 shows the design of a laboratory-strap mould system. Heating elements are placed underneath the cavity and thermocouples are fitted close to the mould walls to measure the heat flow from the melt into the steel mould. A lug holder was used to fix and to reproducibly dip down up to three lugs which were cast with thermocouples inside. An additional free thermocouple was added to measure the temperature in the melt during cooling and solidification of the strap. The dimensions of the model strap cavity are 40 mm × 40 mm × 28 mm, and those of the lugs 20 mm × 80 mm × 6 mm.

The node geometry of the finite-element model (a quarter of the volume is sufficient using symmetry rules) of this system is given in Fig. 2 together with representative measured and simulated temperature–time curves at positions in the centre of the lug and in the strap volume. The simulated curves of several experiments were fitted iterative to the measured ones to obtain effective mean values of the heat-transfer coefficients for the heat flow from the melt to the lugs and to the mould walls and for the heat conductivity of the melt.

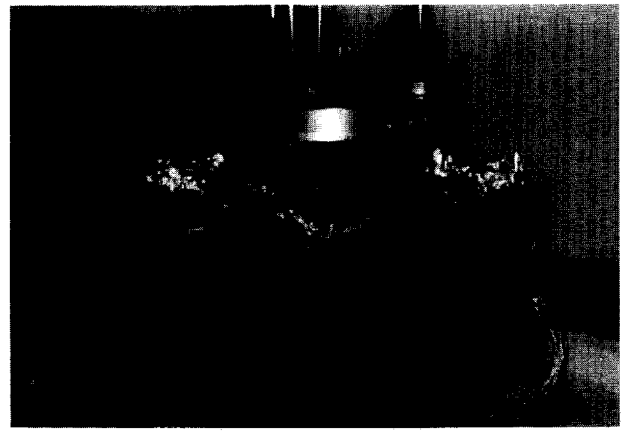

Fig. 1. Laboratory-scale COS apparatus with lug holder, cavity dimensions 40 mm × 40 mm × 27 mm.

It was evident during this work that it is not sufficient to use literature data for these thermophysical quantities because they are usually measured under stationary conditions. The dynamic convective motion after pouring the melt into the cavity is increasing both the effective heat conductivity of the melt itself and the heat transfer to the mould walls and to the lugs. In addition, the heat transfer from the melt to the mould is dependent on the thickness and the condition of the sprayed cork layer. The approach to use mean values without any temperature dependence was found to be a reasonable way to get satisfactory agreement between the measured and the simulated temperature–time curves, especially during the first seconds after dipping the lugs. This is again a simplification of the real situation and will affect the validity of any quantitative result.

The same procedure was used to fit the results of two- and three-dimensional models of full SLI straps to the measured temperature–time curves. In most cases it is sufficient to use a two-dimensional model by increasing the effective heat-transfer coefficient to take into account the difference of the geometrical module (i.e the volume/heat-transfer area ratio). But full three-dimensional models are necessary to investigate geometrical parameters such as the effect of misaligned lugs or different strap designs. More details of our approach to set up a COS model are given in Ref. [6].

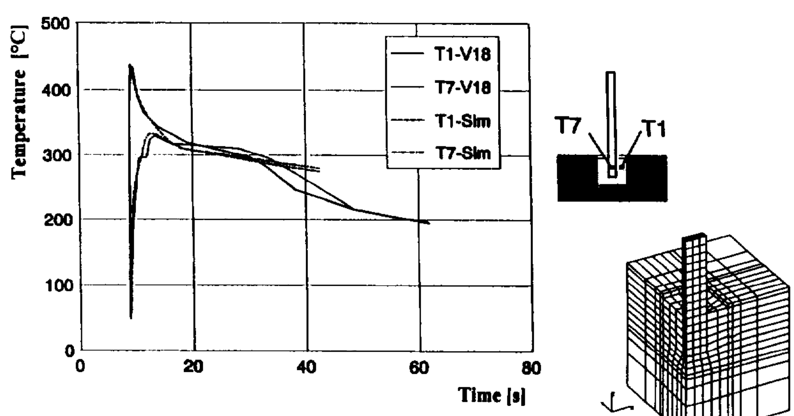

Fig. 2. Node model of the COS apparatus and comparison of measured and fitted temperature–time curves.

3. Results and discussion

If the heat input is sufficient to increase the temperature to the melting point level, the lug tips will melt to a certain extent after having dipped the lugs into the strap melt. A good degree of fusion between the lug and strap material might result even without any melting of the lug only by wetting the lug surfaces with melt material followed by heterogeneous nucleation and solidification.

From our experience, if the temperature of the melt is too low to melt the tip a higher risk for a lack of fusion can be observed. Whether it works or not will depend for a great deal on the actual condition of the lug surface and the degree of wetting. A complete melting of the lug tip indicates a reasonable heat input to the whole lug, and it has a higher probability of producing good fusion quality.

Therefore, we decided to use the value of the backmelting distance as defined in Fig. 3 to present the impact of the process parameters to the expected quality of fusion. In this definition, cold joints will be represented by a backmelting distance equal zero and an overheated condition will be indicated by a backmelting distance equal or greater than the depth of insertion. By plotting lines of constant temperature

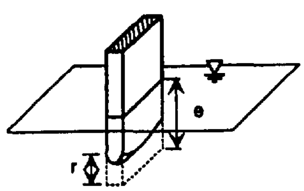

Fig. 3. COS process scheme with definition of dipping depth, *e*, and backmelting distance, *r*: cold joints are represented by $r=0$ and an overheated condition is indicated by $r \geq e$.

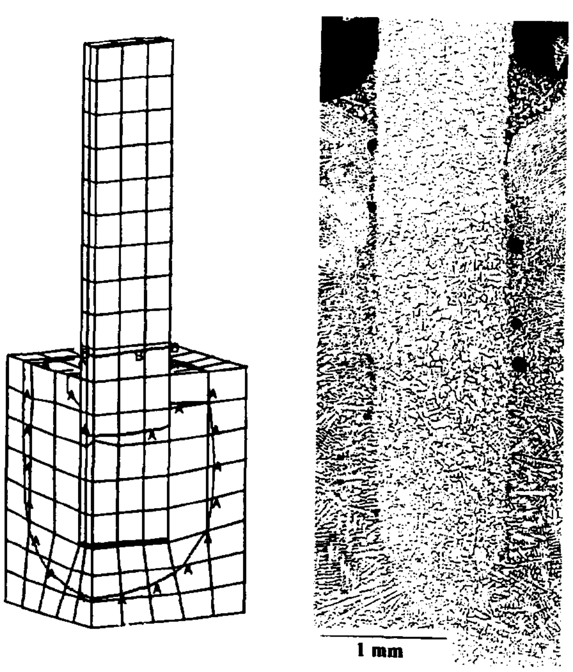

Fig. 4. Finite-element model of one lug (isotherm lines A: 311 °C, B: 255 °C) compared with the metallographic section of a lug/strap joint in an SLI strap.

(e.g. the isotherm of the melting temperature of the lug alloy) in the node model at certain time steps after dipping it is possible to detect the exact time of complete melting and to estimate the maximum backmelting distance under the conditions of a simulation run.

Fig. 4 gives a plot of a single lug finite-element model at the moment of maximum backmelting together with a metallographic section of a typical lug in a SLI battery strap. The lines A and B are representing the liquidus and the eutectic temperature of the lead–antimony grid alloy.

The main heat flow is directed from the hot melt into the cold lug. As a detail, the model is predicting a very fast cooling and solidification of a small melt zone in the corner between lug and melt surface. The main part of the strap melt is solidifying much slower resulting in a lower volume percentage of material with eutectic composition. This is responsible for the differences in microstructure which can be seen in the metallographic micrograph.

As examples showing the benefit of using a COS simulation in practice, results of the systematic variation of some of the process parameters are given in terms of the resulting backmelting distance. Fig. 5 shows the basic three-dimensional node model used to simulate a complete SLI COS-strap joining seven plates. The dimensions of the strap part joining the lugs are 6 mm × 18.5 mm × 40 mm. The thickness of a lug is 0.9 mm. All results presented here refer to a Pb–Sb strap alloy and a Pb–Ca–Sn grid alloy. The distance of backmelting was measured at the centre line of the lugs.

Fig. 6 gives the distance of backmelting versus the initial melt bath temperature for three lugs of this model. Raising the initial melt temperature will in general increase the melted volume portion of the lugs represented by the backmelting

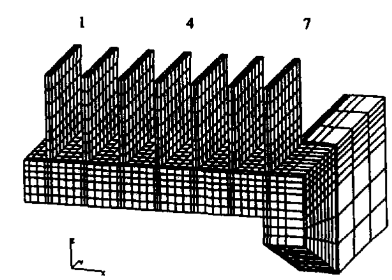

Fig. 5. Three-dimensional finite-element model of a typical SLI battery strap.

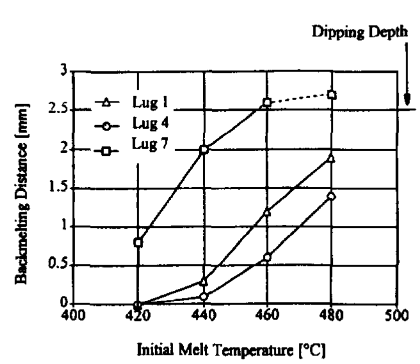

Fig. 6. Backmelting distance vs. initial melt bath temperature for lugs 1, 4 and 7 of Fig. 5: dipping depth 2.5 mm, and strap height 6 mm.

distance. The two lugs at the sides of the strap (signed as 1 and 7 in Fig. 5) are melted to a greater extent compared with those in the centre (no. 4 as example) if they take up the heat content of a larger amount of melt as they do in this example. The usable temperature range is small if we do not want to melt the side lug (no. 7) completely which is heated up by much more melt volume than the others. This effect may not be that dramatic in practice, because this part of the melt starts cooling first during filling the mould.

The initial cooling rate of the strap melt is extremely rapid immediatly after pouring (> 100 K/s) and the delay time between pouring and lug insertion has to be controlled very carefully to avoid overheated or cold joints. The temperature difference between the inserted lug volume and the surrounding hot melt immediatly after dipping is the driving force for the heat flow into the lug. The temperature of the melt at the moment of insertion is therefore, in our view, the most decisive factor for the thermal history of the process and for the resulting quality of fusion. The heat transfer to the lugs is very fast if the surfaces are clean and allow a complete wetting. The first two seconds after dipping are decisive for the temperature increase and the resulting quality of fusion. The remaining process time is needed for cooling and solidification of the strap body.

The mould temperature, when compared with the melt temperature, has only a minor influence on the melting depth of the lugs but is the main factor controlling the overall cooling rate of the strap, i.e. the production rate. The conclusions of this part of our simulation program are in good agreement with the results of laboratory-scale data presented in Ref. [4]. The important practical consequence is that it is possible to improve the fusion quality by increasing the initial melt temperature without running to the disadvantage of significant increased process time. The simulation model can be used to get a first estimation of the time necessary for a complete solidification of the strap.

Another important parameter during the production process is the insertion depth; it is not obvious how critical this parameter is in terms of fusion quality and how that depends on the temperature. Different insertion depths are causing a different degree in lug melting because different volumes of the cold material have to be heated up. Fig. 7 gives the results for the same three lugs of our example at two different initial melt temperatures. The 45° line in this plot is representing a complete backmelting of the lug up to the level of the melt surface. In fact, we can learn from the simulation how sensitive the degree of backmelting is depending on the combination of actual melt temperature and dipping depth. If the

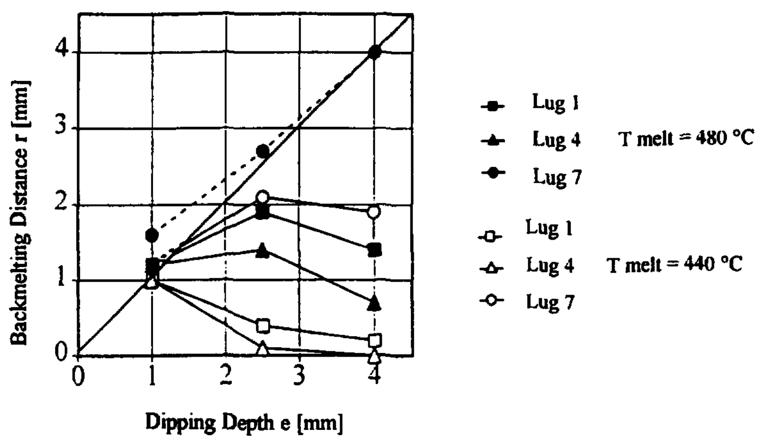

Fig. 7. Backmelting distance vs. dipping depth for the lugs 1, 4, 7 of Fig. 5 at the initial melt temperatures 440 and 480 °C.

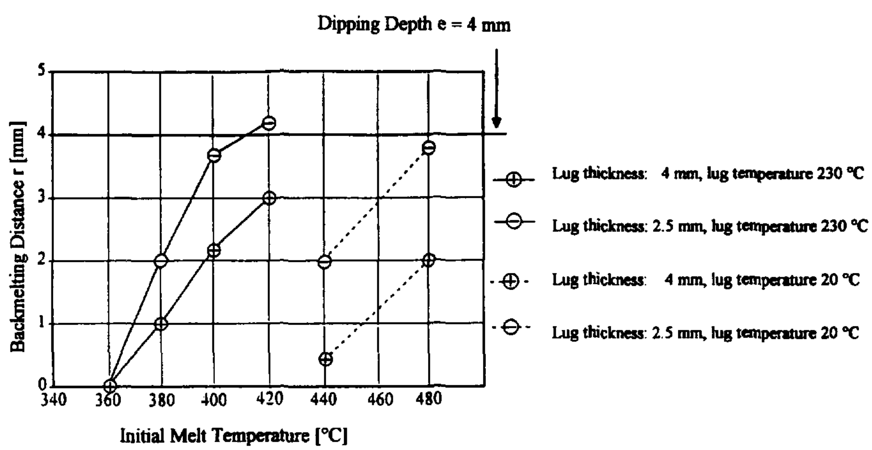

Fig. 8. Backmelting distance vs. initial melt temperature for different lug temperatures and lug thicknesses: dipping depth 4 mm, and strap height 10 mm.

melt temperature is near to the lower limit of the usable temperature range (e.g. 440 °C) the curve in Fig. 7 is showing a very limited range of dipping depths resulting in reasonable backmelting distances. Dipping the lugs to more than one-third of the total strap height will cause little or even no backmelting with the risk of bad fusion. If the insertion depth is reduced to 1 mm the same heat capacity of the strap will cause a total melting of the inserted lug volume. Compared with this situation setting up the initial melt temperature to 480 °C will result in a much more robust process condition and should be preferred.

Both the lug thickness and the lug temperature parameters before dipping are changing the backmelting distance as given in the example of Fig. 8. A typical question in practice is if it is possible to cast on lugs of positive and negative plates with significant different thicknesses using only one melt bath temperature. The diagram can give us an idea of the temperature range which will result in a reasonable degree of backmelting for both types of lugs. If they are not pre-heated, 460 °C would be a good choice.

Preheating the lugs will shift the initial melt temperature range yielding good fusion but avoiding complete backmelting to a much lower level. This is an effect known from using pretinning of the lugs in a tin melt bath immediatly before dipping into the strap melt.

4. Conclusions

1. The simulation of the COS joining process in a finite-element analysis is a valuable tool to get more insight into the thermal aspects and fundamental parameters. After optimization of the model, by adjusting the results to experimental data, can give not only qualitative information but also first quantitative estimations; it can also be used to identify robust process conditions.

2. Interpreting the results in detail we have to keep in mind the basic simplifications of the specific model approach. Differences between the simulated results and the experiental data will help to understand the process and to identify hidden parameters.

3. The simulation was used to investigate the impact of parameters such as initial melt temperature, depth of insertion, lug thickness and lug temperature to the resulting backmelting of the lugs which is, in our view, a criterion for the expected quality of lug/strap fusion.

4. It is important to understand that parameters such as the cleanliness of the lug surfaces or the quality of the fluxing agent are not included in the model; they may affect the quality of fusion in practice.

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