IMPEDANCE STUDIES OF INTER-CELL WELDS IN AUTOMOTIVE LEAD/ACID BATTERIES

Z. STOYNOV*, B. SAVOVA-STOYNOV and T. KOSSEV

Central Laboratory of Electrochemical Power Sources, Bulgarian Academy of Sciences, Sofia 1040 (Bulgaria)

Introduction

The quality of inter-cell welds determines the life and reliability of automotive lead/acid batteries. The fact that poor welds often cause early battery failure demands the introduction of strict quality control procedures during battery production. This, in turn, has resulted in increased interest in the development of more sophisticated methods for conducting quality analysis tests of inter-cell welds.

It is generally accepted that mechanical cutting strength is a measure of weld quality and this approach is widely used as a destructive control test in most battery plants. On the other hand, since it is assumed that there is a direct correlation between the cutting strength and the electrical resistance of the weld, it is considered that resistance measurement — a non-destructive test — can be used as an estimate of weld quality. To investigate the possibilities of this latter approach, impedance measurements have been conducted on inter-cell welds and the results are reported in this paper.

d.c. Measurements

Studies have been carried out on inter-cell welds in two types of plate groups, namely,

(i) welds installed in empty boxes and welded by standard technology;

(ii) welds installed in empty boxes and welded by deliberately inferior technology.

Both groups included welds of small size (55 A h) and of large size (135 A h and 180 A h) automotive batteries. Preliminary measurements showed that the resistance was in the range 4 - 20 $\mu\Omega$ and 2 - 10 $\mu\Omega$ for the two battery sizes, respectively.

The measurement of resistances of the above order is a difficult task and beyond the capability of common commercial equipment. Therefore, special laboratory instrumentation based on the 4-probe method was assembled. The

*Author to whom correspondence should be addressed.

0378-7753/90/$3.50

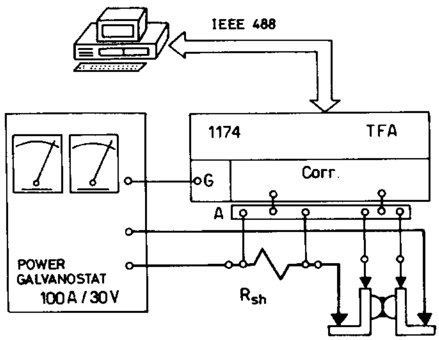

Fig. 2. Experimental facility 'BETATEST-WZ' for impedance measurements of low resistance systems.

error of less than 1%. All other measurements were carried out in accordance with this geometry.

A noise due to the thermal voltages produced between the weld and the sensors, was also present. To overcome this, all d.c. measurements were performed in two stages in which the positions of the voltage sensors were exchanged and the mean value from both measurements was calculated.

Correlation between resistance and external appearance of welds

Before measurement, the features of the welds from each group were inspected and recorded by a qualified engineer. Following this expert evaluation, the same welds were evaluated by the instrumentation described above.

From this comparison, it was concluded that there was a close correlation between the electrical resistance and the splitting of the material. This finding suggests that in some extreme cases even visual observation of the splitting can be used for rough technology control.

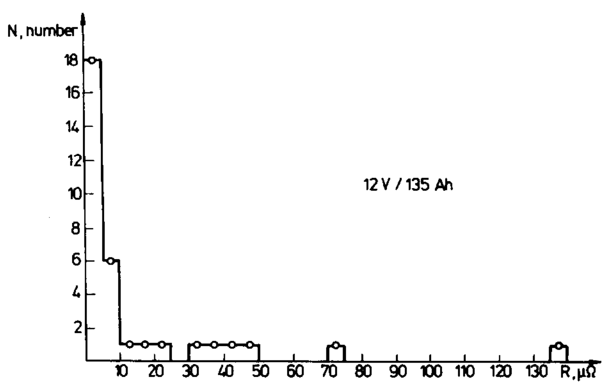

Fig. 3. Histogram of internal resistance of inter-cell welds produced by deliberate application of inferior technology.

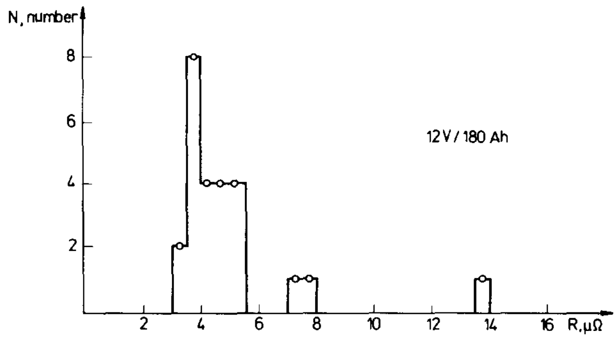

Fig. 4. Histogram of internal resistance of inter-cell welds produced by standard technology.

Results

A number of different size welds and welds produced with standard and inferior technology has been carefully measured by the d.c. instrumentation described above. The results from representative sets are presented as histograms. Figures 3 and 4 show histograms of the resistance distribution of a set of welds (135 A h) produced by inferior and standard technology, respectively. It can be seen that when the standard technology is maintained, the weld histogram has a pronounced maximum and a small distribution of values. The shape suggests that the histogram relates to the Rellay law of distribution rather than to the Gaussian form. Furthermore, a random population exists at very high resistances for both types of weld. Obviously, this behaviour is not due to deviations in the current and time of the welding process.

The following conclusions can be drawn from the above studies:

(i) the resistance values of the welds vary in the 2 - 20 μm range for all standard sizes of battery;

(ii) the working current should be in the 20 - 40 A range;

(iii) the specific four-probe method is essential for this type of resistance measurement; it is sensitive and detects subtle details in the weld technology.

On the other hand, application of the d.c. quality control method to plant operations is inefficient because:

(i) the required d.c. measurement instrumentation (sensitivity of 1 μV) is expensive and unreliable;

(ii) in the battery production line the thermal voltage noise cannot be overcome in the manner described above.

Hence, it is necessary to examine an a.c. approach to the determination of weld quality.

a.c. Impedance measurements

The measurement of high-conductivity systems with resistances of a few μΩ using ready-made impedance instrumentation is not possible. To overcome this difficulty, an in-house facility, 'BETATEST' [1], Fig. 2, has been developed. A specially designed double-channel differential amplifier ($k = 100$) was introduced in front of the Solartron 1174 analyser. The measurements were carried out in a galvanostatic mode with an a.c. current of 25 A using the 4-probe method in the frequency range 100 - 0.1 Hz over 100 periods of integration. To improve the data quality, an additional pre-processing stage was introduced for filtration of the outlying points produced by the mains supply frequency (50 Hz and the harmonics) [2]. The main problem with this kind of measurement arises from the imperfections of the reference shunt; the self-inductance greatly deforms the results.

To find ready-made inductance-free shunts is, in principle, impossible. Obviously, it is necessary to use standard shunts and apply a more sophisticated means of data treatment. The problem has been analysed theoretically and it has been found that the shunt inductance can be calibrated without an inductance-free reference. This technique is based on separate measurements of the impedance of an external load (second shunt) with knowledge of only the active resistance. The load inductance determines the inductive behaviour of the impedance diagram. The latter is, however, typically deformed to the right side with increase in frequency. It can be shown analytically that the deformation is caused by both self-inductances. By applying the formulae

$$L_{sh} = R_{sh}\sqrt{\left[\left(\frac{\mathrm{Im}_1}{\omega_1}\Big/\frac{\mathrm{Im}_2}{\omega_2}\right) - 1\right]\Big/\left[\omega_2^2 - \omega_1^2\left(\frac{\mathrm{Im}_1}{\omega_1}\Big/\frac{\mathrm{Im}_2}{\omega_2}\right)\right]} \quad (1)$$

the unknown volume of L_{sh} can only be calculated on the basis of R_{sh} and the measured data. The application of eqn. (1) to different pairs of frequencies allows validation of both the accepted model and the assumption of combined behaviour of L_{sh} and L_{load}. In the described case, the estimated shunt-inductance is 18.7 nH with a good stability in the frequency range used.

After obtaining L_{sh}, all further measurements were corrected for this value. The good, straight line shapes of the pre-processed diagrams are

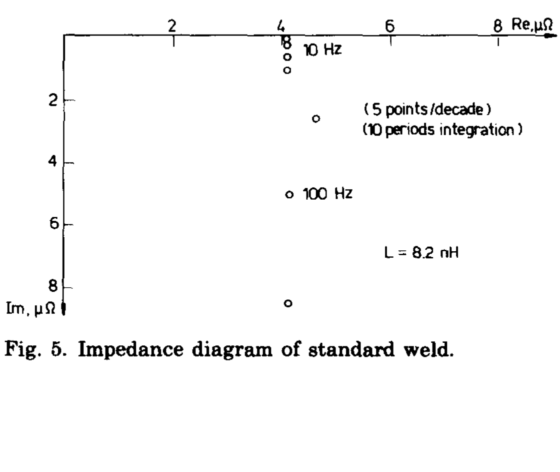

Fig. 5. Impedance diagram of standard weld.

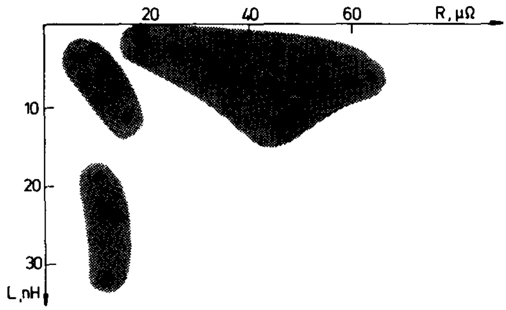

Fig. 6. Dependence of inductance, L, on weld resistance, R, produced by inferior technology for a frequency of 1 Hz.

proof of the validity of the technique. Figure 5 presents the pre-processed impedance of a weld with a clearly defined good quality, as evaluated by the d.c. measurements. A further pre-processing stage will eliminate the outlying points caused by the influence of the main supply frequency.

Analysis of the impedance diagrams of the good welds shows that their inductances are in the range 3 - 20 nH. These values are extremely low, but compared with the low values of R, they produce a significant phase-shift for frequencies higher than 1 - 5 Hz. Thus, the measurements at 50 Hz used in practice are not entirely correct — they estimate the impedance modulus rather than the resistance of the weld.

To clarify the importance of the different parts of the impedance for quality assessment, measurements were conducted on welds obtained using poor technology on all the samples. The individual diagrams have the same shape (as in Fig. 5) but have different values for the real and imaginary parts. To analyse these results, the individual weld inductances were calculated for a number of frequencies. The results for a frequency of 1 Hz are given in Fig. 6. A qualitative cluster analysis of these samples shows that the results can be classified in three phenomenological groups:

(i) good and poor welds with pronounced correlation between R and L;

(ii) distinctly bad welds for which R is very high and L does not correlate with R;

(iii) good welds (low R) with high values of L that are frequency dependent.

Deviations in the weld technology cause changes in the weld properties that are responsible for their impedance behaviour. After cutting the samples from clusters (ii) and (iii), above, it was found that the former have large holes and sometimes inclusions of plastic particles in the welding area. Samples of cluster (iii) have a large-grained crystal structure of the lead alloy with a grain size of 1 - 3 mm. One possible explanation of the inductance frequency dependence is the inter-crystalline aggregation of ligands causing homogeneous electrical current space; this configuration is frequency dependent. The presence of an inter-granular ligand aggregation will lead to an accelerated inter-granular corrosion supported by the mechanical stress, vibrations, and potential differences under which the weld operates. This phenomenological hypothesis is in accordance with the type of failure mode (*i.e.*, intergranular corrosion) observed in practice for the welds.

Discussion

Improved instrumentation has been developed for impedance measurements of systems with resistances in the $\mu\Omega$ range and inductances of nH. This facility includes a power (100 A) galvanostat, additional and precise pre-amplifiers of the measured signals, data pre-processing programs for filtration of the noisy points, and evaluation and correction of the shunt self-inductance.

The impedance study of a set of welds shows that the real impedance part correlates well with the d.c. measurements. The self-inductances of the welds are different, varying in both value and behaviour. For good welds, the real impedance and the inductance correlate well; there is a group of low quality welds (with pronounced splitting of the material) for which the real part of the impedance is high and does not correlate with the self-inductance.

Another group of welds with low real impedance (without splitting of the material) shows increased values of the inductance that vary with the frequency. One possible explanation of this phenomenon is the influence of large-grained crystal microstructure on the behaviour of the inductance. If this relationship is confirmed, then the impedance analysis can be used as a new method for investigating the micro-structure of metallic samples.

The impedance measurements (and their analysis) can be used for improvement and field adjustment of the weld technology. The quality control equipment should operate in the a.c. mode. The frequency must be limited to a few Hz or, if a frequency of 50 Hz is used, the quality control should be based on the separate estimation of the real and imaginary impedance parts.

References

1 Z. Stoynov and B. Savova-Stoynov, *Ext. Abstr., 32nd ISE Meeting, Dubrovnik, 1981*, p. 650.
2 Z. Stoynov and B. Savova-Stoynov, *Ext. Abstr., 166th Meeting of the Electrochem. Soc., New Orleans, 1984*, p. 159.