

Moisture Loss and Regain by Some Basic Flux Covered Electrodes

Investigation relates data on moisture pickup to baking treatment and holding oven efficiency for controlling hydrogen in weld metal

BY B. CHEW

ABSTRACT. Measurements have been made of the effect of baking temperature on the loss of moisture from some SMA electrodes. Data has also been collected showing the influence of atmospheric humidity on the rate of moisture reabsorption, and the effectiveness of holding ovens in suppressing this process. A diffusion model has been applied to the moisture regain results which adequately describes the absorption behavior up to 50% of the saturation value.

Introduction

Crack-like defects in a welded joint can result directly from the introduction of dissolved hydrogen into the weld by the welding process (Ref. 1). Not only may these defects in themselves be of unacceptable size, but even the smaller ones may form sites of incipient cracking which will propagate at a later date under conditions where creep or fatigue can occur.

Where manual shielded metal-arc (SMA) welding of a high quality is carried out, basic flux covered electrodes are generally used. With these electrodes the mineral coating is made to adhere to itself and to the core wire by means of a silicate binder, commonly sodium silicate, and it is this binder that is the source of moisture from which the weld hydrogen comes (Ref. 2).

The need to avoid cracking problems by limiting the hydrogen con-

centrations developed makes it necessary to apply some form of drying or baking treatment to the electrodes before use. Equally, it is necessary to store the electrodes after baking in such a way as to maintain as far as possible the degree of dryness that has been achieved. The second requirement arises since well dried electrodes will tend to take up moisture on exposure to the atmosphere (Ref. 3).

The present work is concerned with these two aspects of electrode treatment and storage. The effect of baking temperature on covering moisture and weld metal hydrogen contents has been studied. Both of these quantities are used in National Standards to specify the hydrogen producing tendency of SMA electrodes (Refs. 4, 5). In addition the rate at which baked electrodes regain moisture when exposed to various controlled humidities was measured, together with data on the amount of moisture uptake occurring at holding oven temperatures.

Finally, the room temperature reabsorption data is rationalized in terms of a diffusion model which is intended to shed some light on the mechanism of moisture uptake by baked electrodes.

Experimental Data

Electrode Baking

All measurements were made on commercially available basic covered electrodes purchased in the normal way from the electrode manufacturers. Two types were examined, the first of these, electrode A, deposited

2CrMo weld metal and the second, electrode B was of the mild steel variety. The electrodes were coded E9015-B3L and E619H.*

A single container of each type was used and all the electrodes, after removal from their containers, were allowed to come to equilibrium with the laboratory atmosphere for many weeks before use. In fact, daily weighings of a sample taken from one of the electrodes indicated that equilibrium was attained within a matter of days rather than weeks, and only small excursions in weight occurred thereafter in response to atmospheric humidity changes. The aim of this was to have all the electrodes in a similar, reasonably stable, starting condition representative of electrodes that had been stored without special precautions under normal conditions of temperature and humidity. Electrodes so treated are referred to subsequently as "laboratory conditioned."

Moisture determinations were carried out on the flux covering in a manner that has been described previously (Ref. 6). The principle of the method involves combustion of the flux sample at 900-1000 C in a stream of pure dry oxygen and absorption of the combustion products in weighed tubes containing an appropriate absorbent for H₂O. Measurements were obtained on samples of both electrode coverings after baking for 1 h at 150, 250, 350 and 450 C. Figure 1 shows the flux moisture content versus temperature of

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*For specifications see AWS A5.5-69 and British Standard 1719: Part 1: 1969, respectively.

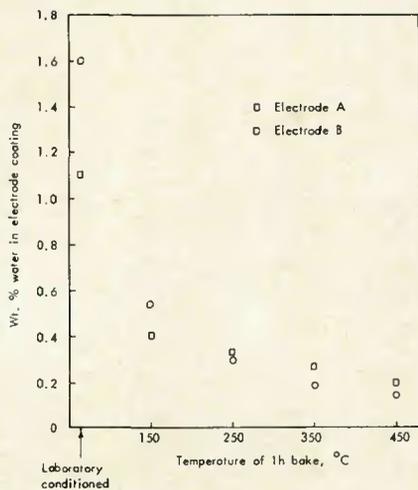


Fig. 1 — Electrode covering moisture content as a function of baking temperature

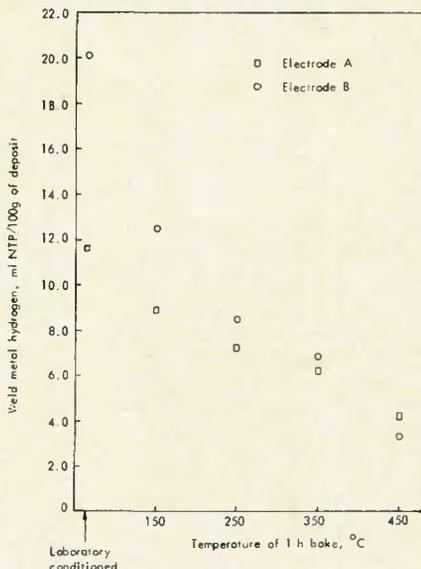


Fig. 2 — Weld metal hydrogen as a function of electrode baking temperature

the 1 h bake. The values used are averages of at least four determinations.

Whole electrodes baked for 1 h at 150, 250, 350 and 450 C were then used for the determination of their weld metal hydrogen according to the procedure given in Ref. 4. On removal from the baking oven, electrodes were transferred rapidly to a sealed metal container for transportation to the welding site where the tests were carried out. It can be shown that the quantity of moisture available in the air space around the electrodes within the container, even if it were all absorbed, is insufficient to sensibly affect the moisture content of the electrode covering. In this way it was assured that the electrodes would not pick up any additional moisture between baking and testing. In Fig. 2 are plotted the weld metal hydrogen contents as a function of the baking treatment. Values shown in this instance are averages of at least six determinations.

Moisture Regain

Measurements were made on the two electrodes referred to above together with electrode C, also designated E619H. Again, a single packet of each type was used and all electrodes were allowed to equilibrate with the laboratory atmosphere. The aim of these experiments was to measure the moisture uptake of samples of electrodes at room temperature under various humidity conditions. A series of constant humidity chambers was set up using dessicators containing saturated aqueous solutions of various salts.

Electrode samples, 35 mm long, were baked for 1 h at 250 C, then stored in sealed containers and weighed. The baking schedule was based on work reported in the previous section and in addition was selected as the treatment that is becoming increasingly used in practice in place of the 1 h at 150 C treatment. Approximately 16 of these samples were transferred rapidly, one at a time, from their containers to the appropriate constant humidity chamber. They were removed at suitable intervals of time and weighed again in their sealed containers. The weight gain represented the quantity of moisture taken up by the sample during its period of exposure at the given humidity. The laboratory temperature did not move outside the limits 20 ± 1 C during these operations.

Separate measurements were made of the covering weight per gram of electrode by stripping the flux from 10 samples of the same kind as were used for the humidity work. Using this information it was then possible to convert the weight gain for a given sample to a percentage increase in the covering weight.

The results are plotted on Figs. 3-5 for electrodes A, B and C.

A further series of experiments was set up to investigate the extent of moisture absorption by baked electrodes when stored in holding ovens at constant temperature. Approximately 20 samples baked at 250 C and weighed as described above, were divided into two groups of ten. One group was placed at time zero in an air circulating oven previously set to the required temperature and at the same time the second group was

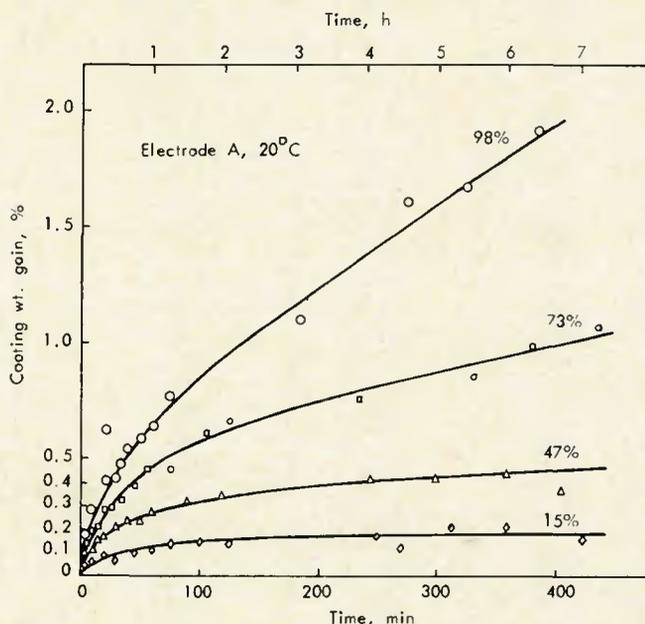


Fig. 3 — Electrode covering weight gain as a function of time and relative humidity after baking for 1 h at 250 C

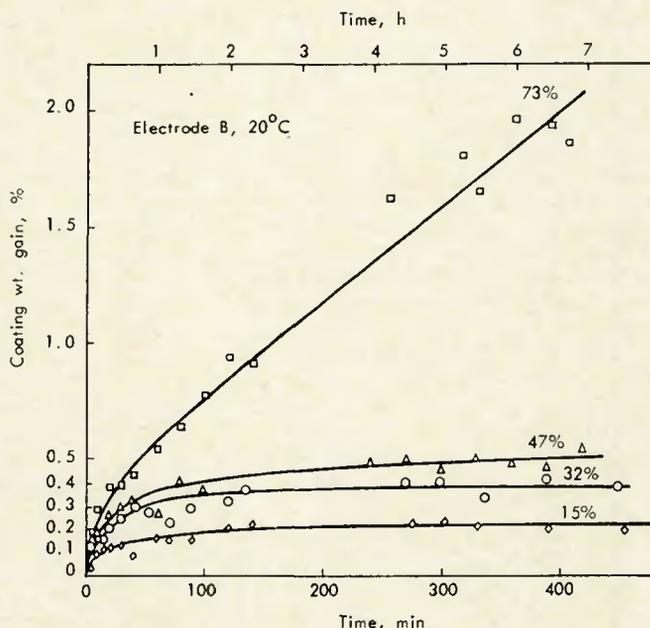


Fig. 4 — Electrode covering weight gain as a function of time and relative humidity after baking for 1 h at 250 C

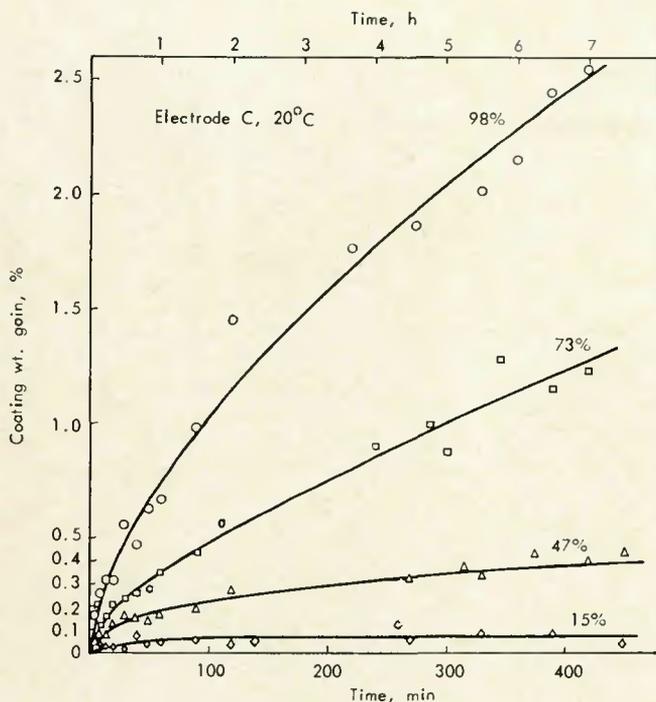


Fig. 5 — Electrode covering weight gain as a function of time and relative humidity after baking for 1 h at 250 C

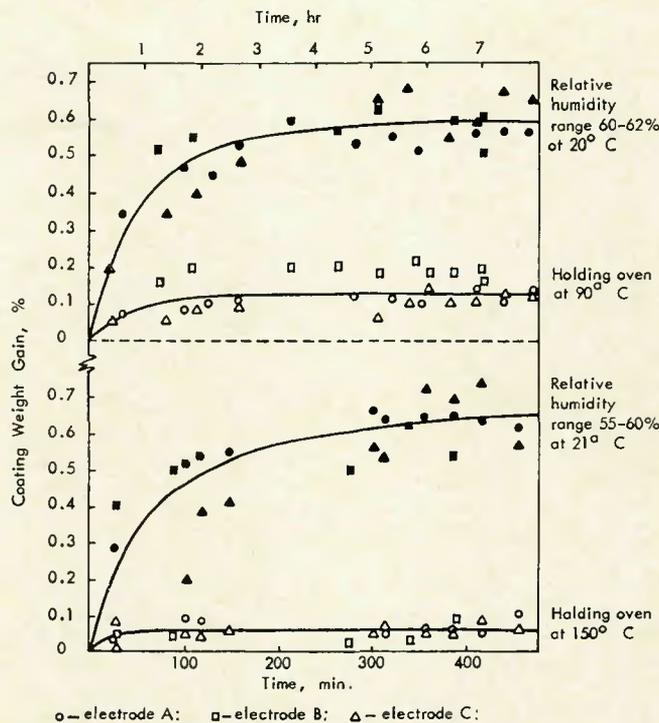


Fig. 6 — Comparison of electrode covering weight gain at room temperature and humidity with that in an air circulation oven at elevated temperatures. Electrode samples baked 1 h at 250 C before use

exposed to the laboratory atmosphere at the ambient temperature for comparison.

At set intervals of time a sample was removed from the oven and returned to its sealed container; at the same time one of the control samples was taken and placed in its container. In this way it was possible to compare the moisture weight gain that had occurred in the holding oven with that which would have occurred had the sample been left exposed to the atmosphere at the ambient temperature and humidity. Figure 6 shows the results of these measurements for the three electrodes.

Discussion

In general, the weld metal hydrogen and flux moisture results show the expected trend that increasing baking temperature gives progressively lower covering moisture content (Fig. 1) accompanied by reduced weld metal hydrogen concentrations (Fig. 2). In framing an overall recommendation to be included in a welding procedure, to be certain of achieving 10 ml H₂ NTP per 100 g weld metal as required at present in the British Standard (Ref. 4), the moisture content for both electrodes should not exceed ~0.4% and 1 h at 250 C would be necessary. It may be shown in a particular case, as with electrode A, that some relaxation of this requirement is possible and in

that case a less stringent baking schedule may be adopted.

However, hydrogen levels ought not to be taken in isolation, but viewed as one aspect of a total welding procedure properly designed to suit the particular application. That is to say, there will be more critical situations where the 10 ml level is inadequate and higher baking temperatures must be used. This is the basis of recent attempts (Refs. 7 and 8) to subdivide hydrogen levels into classes corresponding to the ranges 0-5, 5-10, 10-20 and > 20 ml NTP per 100 g, termed "very low," "low," "medium," and "high." In these cases the recommendations would be 1 h at 450 C for the 0-5 ml range (~ 0.2% moisture) 1 h at 350 C or 250 C for the 5-10 ml range (~ 0.4% moisture), the former obviously being a safer more conservative choice, with 1 h at 150 C needed to bring electrodes into the 10-20 ml class.

It has been shown previously (Ref. 9) that there is a correlation between weld metal hydrogen and flux moisture, and this relationship has been interpreted using chemical thermodynamics (Ref. 10). Figure 7 shows the correlation found in the present work which agrees fairly well with that reported by Moreton, Parker and Jenkins (Ref. 9) and Holmberg et al (Ref. 13). There is less satisfactory agreement with the correlation shown by Smith (Ref. 11) who reports lower hydrogen levels for a given moisture content, particularly at the higher end,

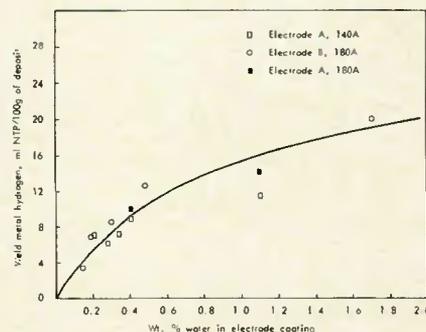


Fig. 7 — Weld metal hydrogen as a function of covering moisture content

than is found in the present work. This could be due to the use by Smith of glycerine as a collecting fluid for hydrogen which has been shown to absorb this gas readily at atmospheric pressure (Ref. 12). In the present work and that of Ref. 9 mercury was used as a collecting medium.

It is possible, therefore, to specify the hydrogen producing tendency of an electrode by reference to its flux moisture content. This is the approach adopted in AWS A5.5-69 and some US Military Specifications in which maximum moisture levels are permitted in electrode coverings depending on the strength level of the deposited weld metal, increasing strength being coupled with decreasing allowable moisture content. This recognizes the fact that sensitivi-

ty to hydrogen cracking is greater in high strength steels than in low.

The disadvantage of this approach is that it does not deal directly in terms of the controlling parameter, namely the weld metal dissolved hydrogen concentration. Further, the thermodynamic treatment (Ref. 10) indicated that two electrodes having the same moisture content could in principle generate different hydrogen contents depending on the quantity of shielding gas produced by decomposition of the metal carbonates in the flux coating. There is some evidence also in Fig. 7 that welding current can affect the hydrogen concentrations developed so that differences can be obtained again at the same moisture content, although the differences observed in this work were not large.

It must be stressed again that proper storage of electrodes after baking before use is essential to realize the benefits of any baking procedure. It was with this in mind that the moisture uptake measurements shown in Figs. 3-5 were made. The extent of absorption at high humidities, $\geq 73\%$, for all three electrodes is large and shows little tendency to flatten out with increasing time during the period of the experiments. At $\leq 47\%$ humidity there is a tendency for the uptake to level off after perhaps ~ 100 min. However, the extent of reabsorption after this time at which the electrodes could be said to be in a nearly stable condition, is unacceptably high.

For example, electrodes A and B have taken up some 0.4-0.5% moisture at 47% which must be added to the $\sim 0.3\%$ already present after the 250 C bake, Fig. 1. This results in a total moisture content in the region of 0.7-0.8% which is greater for example than that remaining after a 1 h at 150 C bake, $\sim 0.5\%$. Thus, the beneficial effect of the 250 C bake has been lost and the electrodes now have a moisture content lying between that after a 150 C bake and the original "laboratory conditioned" state, which was 1.1% for electrode A and 1.6% for electrode B.

Electrode C, whose baking characteristics were not studied, showed similar uptake behavior to the other two, with perhaps slightly less absorption in the time available at the lower humidities. Clearly, the rate of uptake shown in Figs. 3-5 is such that it would be impossible to use baked electrodes that had been allowed to cool to ambient (20 C) quickly enough to prevent significant moisture reabsorption.

Several measurements of moisture absorption rate by SMA electrodes are reported in the literature. In the most recent of these Miller (Ref. 14) describes the effect of relative

humidity at 28 C and 40 C for the case of thirteen commercial electrodes which fall into either the E7016 or E7018 categories. Higher absorption rates were found at 40 C than those at 28 C, presumably because at the higher temperature not only is the kinetic process accelerated but the atmosphere is able to hold a greater quantity of moisture. The present measurements refer to a lower temperature (20 C) so that a direct comparison between the two sets of results is not possible. However, absorptions of comparable magnitude at similar times are obtained, with those in this work being somewhat lower as might be expected.

Other measurements of moisture uptake found in the literature (Refs. 11,15,3) have generally been obtained over a time scale of 100-200 h and detailed information covering the much shorter times of interest here is sparse. However, as far as can be judged from the initial portions of these curves uptakes of the same order as those reported in this and Millar's work were obtained.

Thus, the electrodes studied reabsorb moisture in significant amounts relatively quickly, and therefore it was necessary to examine how reabsorption could be suppressed by oven storage at higher temperatures. Initially 90 C was chosen and it was found that even at this temperature, for electrodes A and C, Fig. 6, 0.1% moisture was taken up and for electrode B, reabsorption amounted to some 0.2%. For comparison, the extent of the coating weight gain at the prevailing temperature and relative humidity was also measured using the control samples and is plotted with the appropriate holding oven results.

Since a regain of 0.2% moisture would be equivalent to a return to the 1 h at 150 C baking position of 0.5% total moisture, the uptake at 90 C is still higher than is desirable, although the benefits of the holding oven storage compared with exposure to the atmosphere are clearly demonstrated.

Accordingly, similar measurements were made with the holding oven at 150 C. The results of these experiments show generally a final average moisture regain of about 0.05%. Whilst still representing a finite increase this is a reasonable compromise, short of storing electrodes at the original baking temperature at 250 C in order to completely suppress the reabsorption of moisture.

Several further points should be made. The use of an oven equipped with air circulation allows the electrodes to come to equilibrium at the holding oven temperature with the partial pressure of water vapor prevailing in the atmosphere at the time

of the experiments. In fact, holding ovens not equipped with air circulation will be preferable since a lower partial pressure of water vapor will prevail in them if moisture is taken out of the oven atmosphere by absorption into the electrode covering. This is in contrast with the electrode baking situation where air circulation is beneficial, since it will help to remove evolved moisture from the vicinity of the electrodes.

In holding oven experiments the humidity of the air entering the oven was not fixed and this was one of the reasons for using a series of control samples simultaneously. The levels of humidity during the experiments which were carried out during the summer months were fairly high, $\sim 60\%$ at 21 C. Thus the data were obtained under somewhat humid conditions and electrode storage precautions based on them would be adequate also for the lower humidities that are found, for example, during the winter months.

The results throughout refer to electrodes that have been baked for 1 h at 250 C. This is not the most severe schedule that could be applied. It has been shown earlier that still lower moisture levels can be obtained by baking for 1 h at 350 C or even 450 C. These latter treatments will be called for in critical welding situations where the risk of hydrogen induced cracking is high, e.g., where there is a high carbon equivalent, high restraint, thick joint, etc. There is a need, therefore, to carry out a similar investigation on electrodes that have been baked at these high temperatures, with the aim of retaining the degree of dryness achieved.

Finally, the absorption results cover only a limited number of electrodes, humidity and temperature conditions. They may, however, be regarded as typical and demonstrate clearly the importance of giving careful attention to the handling and storage of baked electrodes.

Moisture Absorption Model

In this section the moisture absorption data are interpreted in terms of diffusion theory. From this treatment it was hoped to gain some insight into the mechanism of moisture uptake by these electrodes and, as is usual with diffusion models, to be able to predict uptakes for other covering thicknesses and electrode sizes, and the distribution of moisture across the covering thickness during the uptake process. Moisture is assumed to exist at the surface of the sample at all times and diffusion into the covering takes place until the concentration gradient is removed. In mathematical

terms a solution to Fick's equation is required:

$$\frac{\delta C}{\delta t} = \frac{1}{r} \cdot \frac{\delta}{\delta r} \left(\frac{rD\delta C}{\delta r} \right) \quad (1)$$

which will satisfy the boundary conditions

$$C = C_0 \text{ at } r = b$$

for all t

$$\frac{\delta C}{\delta r} = 0 \text{ at } r = a$$

where a is the radius of the core wire and b is the overall radius such that the covering thickness is $b-a$. The second condition above expresses the fact that the inner surface is impermeable to transport of moisture. It

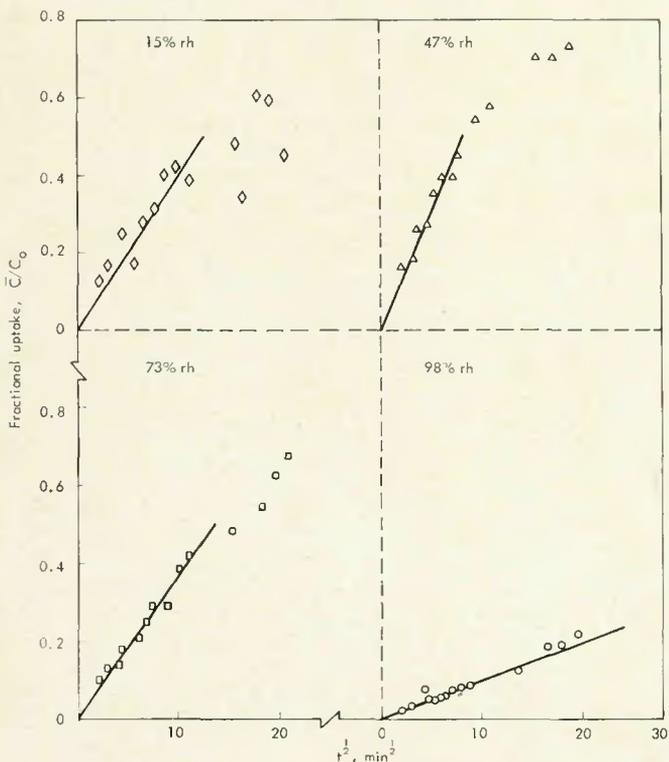


Fig. 8 — Fractional uptake at several humidities plotted against $t^{1/2}$ according to equation (3) — Electrode A

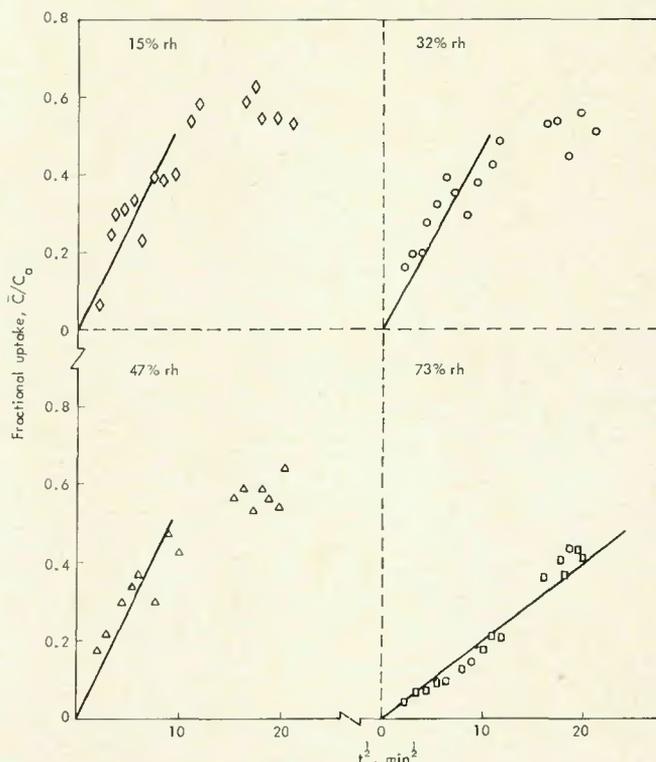


Fig. 9 — Fractional uptake at several humidities plotted against $t^{1/2}$ according to equation (3) — Electrode B

Table 1 — Equilibrium Uptake of Moisture for Various Relative Humidities at 20 C

Elec-trode	98% rel. humidity			73% rel. humidity			47% rel. humidity			32% rel. humidity			15% rel. humidity				
	Time, days	Wt. gain %	Avg wt. gain % ^(a)	Time, days	Wt. gain %	Avg wt. gain % ^(a)	Time, days	Wt. gain %	Avg wt. gain % ^(a)	Time, days	Wt. gain %	Avg wt. gain % ^(a)	Time, days	Wt. gain %	Avg wt. gain % ^(a)		
A	4	6.60	9.13	1	1.25	1.60	1	0.53	0.61				4	0.30	0.35		
	6	8.88		2	1.58		2	0.63					6	0.35			
	6	8.43		3	1.58		3	0.59					6	0.33			
	7	9.53		5	1.55		5	0.53					7	0.41			
	7	9.70		7	1.65		7	0.68					7	0.33			
B				4	4.24	4.59	1	0.57	0.87	4	0.77	0.76	1	0.24	0.39		
				6	4.45		2	0.61		6	0.76		2	0.32			
				6	4.24		5	0.85		6	0.67		5	0.38			
				7	4.49		6	0.81		7	0.80		6	0.39			
				7	5.19		7	0.94		7	0.80		7	0.39			
													15	0.83			
													15	0.70			
C	3	4.68	5.31	3	3.94	4.17	3	0.60	0.80				3	0.37	0.22		
	4	4.81		4	4.24		4	0.70					4	0.18			
	5	4.89		5	4.27		5	0.86					5	0.28			
	6	5.19		6	4.39		6	0.73					5	0.22			
	6	6.01		6	3.88		6	0.79					5	0.19			
	6	4.92		6	4.01		6	0.89					6	0.23			
	7	5.56		7	4.30		7	0.75					7	0.17			

(a) These averages refer to data obtained from day 5 onwards.

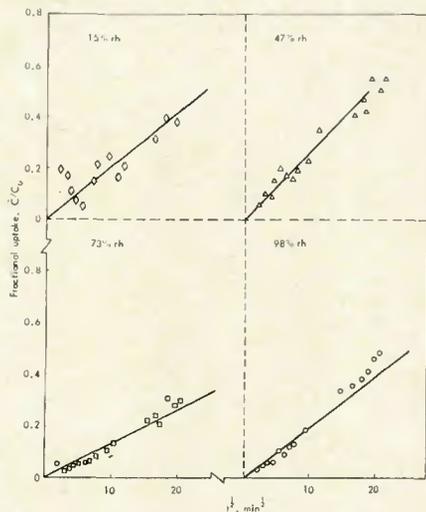


Fig. 10 — Fractional uptake at several humidities plotted against $t^{1/2}$ according to equation (3) — Electrode C

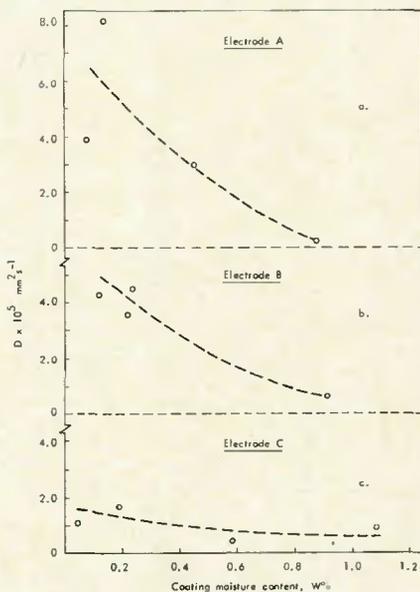


Fig. 11 — Diffusion coefficient as a function of moisture content

has been shown elsewhere (Ref. 16) that the direct analytical solution of equation (1) for these boundary conditions is too cumbersome for easy application and a numerical method using the technique of finite differences was adopted in preference.

As a check on the validity of the procedure the technique was applied to a parallel-sided slab with one face impermeable for which there is a well known, relatively simple analytical solution (Ref. 17) with tabulated values of \bar{C}/C_0 as a function of Dt/L^2 . \bar{C} and C_0 are the average concentrations at time t and infinity respectively and Dt/L^2 is a dimensionless parameter where D is the diffusion coefficient and L is the thickness of the slab. Close agreement between

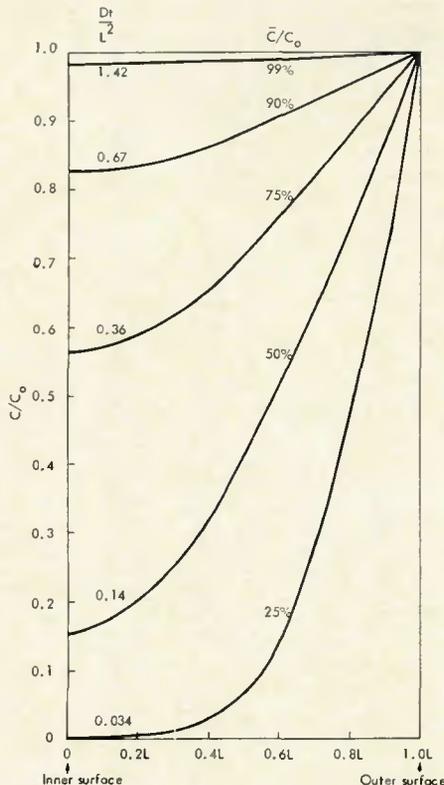


Fig. 12 — Calculated moisture distribution across covering of thickness L

Table 2 — Diffusion Coefficients for Moisture Transport Through Electrode Coverings at Various Humidities

Rel Humidity %	Diffusion coef., mm^2s		
	Electrode A	Electrode B	Electrode C
98	1.55×10^{-6}	—	6.41×10^{-6}
73	2.25×10^{-5}	4.30×10^{-6}	2.89×10^{-6}
47	6.19×10^{-5}	3.14×10^{-6}	1.18×10^{-5}
32	—	2.51×10^{-5}	—
15	2.95×10^{-5}	3.01×10^{-6}	7.44×10^{-6}

the analytical and finite difference results for the slab was obtained which gave confidence in the validity of the method of finite differences when applied subsequently to the cylindrical geometry of the electrode.

It was found that the \bar{C}/C_0 values when plotted as a function of $(Dt/L^2)^{1/2}$, where L is now the covering thickness, gave an excellent approximation to a linear form with a correlation coefficient of 0.9996. Thus, the finite difference technique resulted in the following equation relating fractional concentration to time, coating thickness and diffusion coefficient,

$$\frac{\bar{C}}{C_0} = \frac{1.342D^{1/2}}{(b-a)} \cdot t^{1/2} \quad (2)$$

The data obtained previously are now treated in terms of equation (2).

Application of Model

The results obtained for the quantity of moisture taken up by the electrode samples at 20°C appear in Figs. 3-5. For the present calculations uptakes approximating to infinite time are required. Therefore, a series of additional uptakes were determined on samples which were left for several days to come to equilibrium with the various humidities studied.

These results appear in Table 1 together with average values of those results taken beyond 5 days exposure. This period was deemed to be sufficient to ensure that at least 90% of the equilibrium uptake had been reached. Unfortunately this assumption could not be checked until after the data had been obtained since values of the diffusion coefficient are required to do this. However, for 90% uptake it can be shown (Ref. 16) that a Dt/L^2 value of 0.71 is required. Inserting 5 days for t and 1.35 mm for L leads to a D value of $3.0 \times 10^{-6} \text{mm}^2\text{s}^{-1}$. Most of the diffusion coefficients listed in Table 2 are greater than this, several are of the same order and only one of them, electrode A at 98% relative humidity, is less.

Therefore, it is concluded that most of the final average uptakes in Table 1 represent > 90% of the equilibrium value. Additionally, the results after 5 days do not show, within the precision of the measurements any consistent increase after this time.

Values of the ratio \bar{C}/C_0 were calculated by taking the % weight gain at various times and dividing these by the weight gains corresponding to the steady state from Table 1. In this way graphs of \bar{C}/C_0 as a function of $t^{1/2}$ were obtained as shown in Figs. 8-10. These plots correspond to equation (2) and the straight lines have been fitted by the method of least square applied to the data up to 50% uptake.

Knowing the thickness of the electrode covering from measurements on whole and stripped samples enables diffusion coefficients to be calculated from the slopes of these lines. These coefficients appear in Table 2.

Discussion

In general terms it can be seen from Figs. 8-10 that fair agreement with the diffusion model is obtained. This agreement is best over the first 50% or so of moisture absorbed but after this point values lower than those predicted are obtained for electrodes A and B at all but the highest humidities studied. This is interpreted on the diffusion model by saying that the effective diffusion coefficient decreases with increasing con-

centration of moisture. Examples of concentration dependent diffusion coefficients are common in the literature; see for example Barrer (Ref. 18).

On Figs. 11a and 11b are plotted the diffusion coefficients as a function of concentration. The value of concentration used for each point was the midpoint of the range over which the straight lines on Figs. 8 and 9 were fitted and from which the D values were obtained. Although Figs. 11a and 11b show a good deal of scatter the results do indeed suggest a decrease in D with increasing concentration.

In contrast with electrodes A and B, the plots for C, Fig. 10, show a reasonable fit with the model over the entire concentration range studied. Further, when D is plotted against concentration, Fig. 11c, hardly any variation is found. In this case then, D appears to depend less on concentration than in the other two cases. The reason for this is obscure particularly since the concentration ranges over which the data apply are similar. Further investigation of this problem is hampered by a lack of information on the physical make-up of these commercial electrodes and in what respect they differ from one another. The kind of information required would be, for instance, the particle size distribution of the constituent minerals and ferroalloys, source and nature of these, quantity and type of silicate binder used, and finally the pore size distribution of the finished covering.

The latter would be necessary in order to treat the problem in a more complex manner using a model based on diffusion coupled with adsorption onto internal surfaces. The present situation, however, appears to be more complex than the usual case of diffusion through porous media. There, the nature of the adsorption isotherm plays an important role and diffusion coefficients of the order of $10^{-2}\text{mm}^2\text{s}^{-1}$ are obtained. These correspond to a process either of gas phase diffusion down a pore or diffusion along a film on the pore surface. In the present case we have D values of the order of $10^{-5}\text{mm}^2\text{s}^{-1}$ which are more indicative of transport through a crystal lattice. Thus, any detailed mechanism for moisture transport through these coverings is likely to be complex. This makes the simplified diffusion approach attractive because it reduces this complexity to a single D value which, together with the equilibrium uptake C_0 , enables predictions of moisture reabsorption to be made.

As mentioned earlier these simple predictions are reliable for at least the first 50% of moisture taken up. The

usefulness of the data is in relation to hydrogen cracking problems, and in this context the range of moisture adsorption involved up to this 50%, particularly at normal humidity levels, more than covers the range of interest. Beyond this point, and in some cases well before, the electrodes have become too 'wet' to be used and the rate of uptake becomes of academic interest only.

For electrodes of other sizes provided the ratio b/a remains constant, similar predictions can be drawn up using the parameter Dt/L^2 with L the new covering thickness and assuming the same diffusion coefficient and equilibrium value for the covering moisture content.

A further prediction can be made regarding the distribution of moisture throughout the covering thickness. The general curve, given in Fig. 12, comes from the finite-difference results and shows the fractional concentration plotted across the covering thickness. On each curve are given the Dt/L^2 value and the average concentration, \bar{C}/C_0 , at that value.

These master curves may be converted to represent individual electrodes at given % humidities as follows. Taking electrode A at 47% humidity and knowing the average equilibrium weight gain, C_0 , from Table 1 gives values for the ordinate C as a function of distance across the covering at particular values of Dt/L^2 . These latter may be converted to actual times knowing the diffusion coefficient from Table 2 and the covering thickness. Each of the curves represents also average concentrations which again may be obtained knowing C_0 .

Several comments can be made on these curves. On the basis of the diffusion treatment it appears that the moisture content is not uniform across the covering during moisture reabsorption. For example, when the average concentration is 50% of the final value, the moisture level at the inner surface is still only 15% of the final amount, whereas close to the surface 90-100% is reached. This raises the question of whether all or only part of this moisture appears as hydrogen in the weld pool. That is to say would a moisture concentration corresponding to 50% saturation, if evenly distributed across the covering, result in the same weld metal hydrogen level as would be obtained from a distribution such as is shown in Fig. 12. No experimental evidence on this point exists at the present time.

The actual values for D obtained in this work range between $0.16 \times 10^{-5}\text{mm}^2\text{s}^{-1}$ and $6.2 \times 10^{-5}\text{mm}^2\text{s}^{-1}$ and are similar in magnitude to results quoted by Barrer (Ref. 18) 0.7

$\times 10^{-5}$ to $6.0 \times 10^{-5}\text{mm}^2\text{s}^{-1}$, depending on the concentration, for the diffusion of moisture through zeolites. These minerals have an open structure formed by the linking of SiO_4 tetrahedra, with some of the Si atoms replaced by Al atoms. The present diffusion coefficients are in accord therefore with the idea that moisture uptake by basic flux covered electrodes is attributable in the main to adsorption by the silicate network forming the binder which holds the coating together and to the core wire.

Conclusions

1. To ensure that electrodes generate < 10 ml $\text{H}_2/100$ g deposited weld metal ($\sim 0.4\%$ moisture) as required by the present "hydrogen-controlled" condition of BS1719 a baking treatment of at least 1 h at 250 C is necessary. To achieve levels of 0-5 ml ($\sim 0.2\%$ moisture) 1 h at 450 C is required.

2. The commonly used baking schedule of 1 h at 150 C achieves a significant moisture reduction in damp electrodes but cannot guarantee hydrogen levels to the "hydrogen-controlled" criterion. More probably, values lying in the range 10-15 ml NTP per 100 g (~ 0.4 - 0.7% moisture) would be obtained after such a treatment.

3. A rapid and significant uptake of moisture occurs when basic flux covered manual metal arc electrodes are exposed to relative humidities in the range, 15-98%, at room temperature after baking for 1 h at 250 C.

4. When electrodes are kept in an air circulating holding oven at 90 C sufficient reabsorption of moisture occurs to reduce the effectiveness of the 250 C drying treatment to that equivalent to a 150 C treatment.

5. With the holding oven at 150 C moisture regain is kept to an acceptable level. At both temperatures the air entering the oven had a relative humidity in the range 55-62% at 20-22 C.

6. In general terms, the advantage of using a holding oven is clearly demonstrated by a comparison between the uptake experienced by the control samples kept in the laboratory atmosphere and those in the oven.

7. Over the range of humidities 15-98% at 20 C a diffusion model forms a rational framework for the uptake of moisture by some basic flux covered electrodes up to 50% of their saturation value.

8. The values found for the diffusion coefficient are consistent with the assumption that moisture absorption by these electrodes occurs through the silicate binder material.

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