EFFECTS OF CARBONACEOUS RODDING MIX FORMULATION ON STEEL-CARBON CONTACT RESISTANCE

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Summary

Interface resistance between steel and prebaked carbons as well as carbonaceous mixes was measured in the laboratory as a function of temperature and contact pressure. The latter was determined over the temperature range 50 to 850°C on a production-size steel stud/prebaked anode carbon joint assembly. By altering the mix composition linear shrinkage of rodding mixes could be varied between 0.4 and 0.05%. Corresponding contact resistances were calculated using the experimental data. It is concluded that for a typical steel/carbon rodded joint carrying 3.2 kA current contact voltage drop can be reduced by up to 50 mV when rodding mix formulation and shrinkage are optimized.

Introduction

The purpose of the investigation reported here was to identify the contact resistance between steel and carbon in mix rodded joint assemblies. To this end a laboratory apparatus was constructed in which interface resistances could be measured over a selected range of temperatures and mechanical loads. These resistances are lower than those reported in the literature for production size joint assemblies[1] since the latter include a certain amount of spreading resistance depending on the location of voltage probes used in the measurements. A good knowledge of the true contact resistance is important in minimizing voltage drops between steel and carbon by joint assembly design changes or by altering the rodding mix formulation. Data on cast iron rodded joints exist in the literature,[2,3,4] but the information on mix rodded joints is scarce.

Experimental

Interface Resistance Measurements

The experimental set-up is shown in Figure 1. A 50 mm diameter and 50 mm long sample of steel and of carbon are placed between two graphite rods inside a ceramic protective sleeve. All contacting surfaces are machined rectangular and smooth. The samples and the sleeve are pre-drilled to receive voltage probes. These and thermocouples are installed as shown in the drawing. The assembly is then placed into a vertical furnace equipped with resistance heating elements. The apparatus is now positioned in a hydraulic press so that the graphite rods act as pistons transferring the load to the steel-carbon contact. The press is equipped with a pressure regulator which assures constant load during measurements at the selected pressure. The apparatus can be operated up to 900°C temperature and 100 kg/cm^2 pressure. A current density of 7 A/cm^2 was selected for the measurements. The top and bottom of the furnace was sealed with fiberfrax packing and a nitrogen purge was used to prevent oxidation inside the furnace.

Contact resistance results were expressed in $ohm.mm^2$ units. Figure 2 illustrates the method of calculation used in (a) steel-carbon, (b) steel-rodding mix and (c) carbon-rodding mix contact resistance measurements. In cases (b) and (c) a layer of rodding mix was sandwiched between two samples of steel or two samples of carbon, respectively.

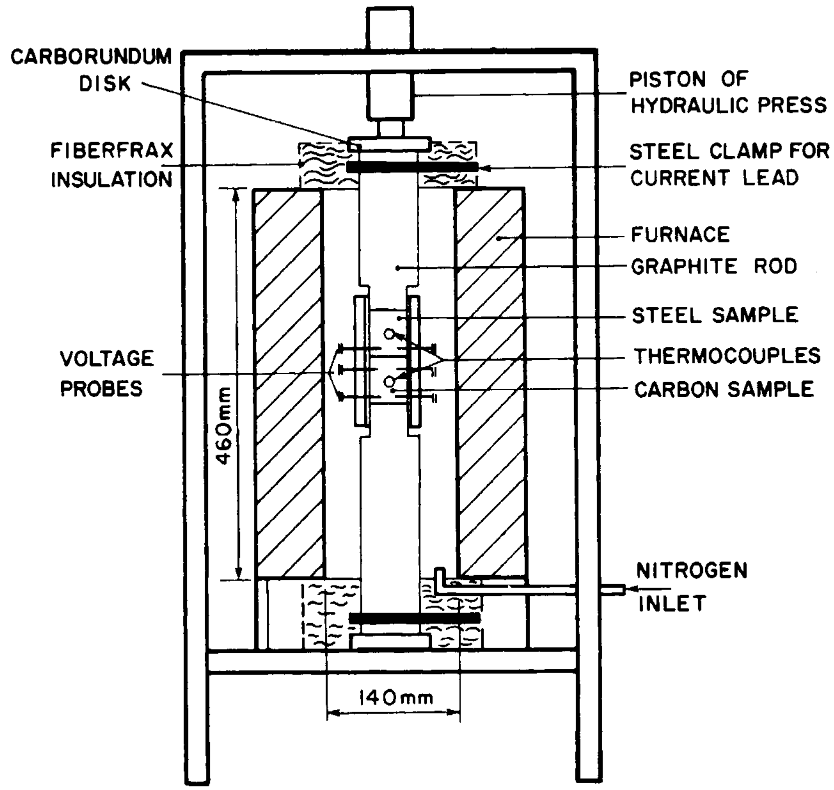
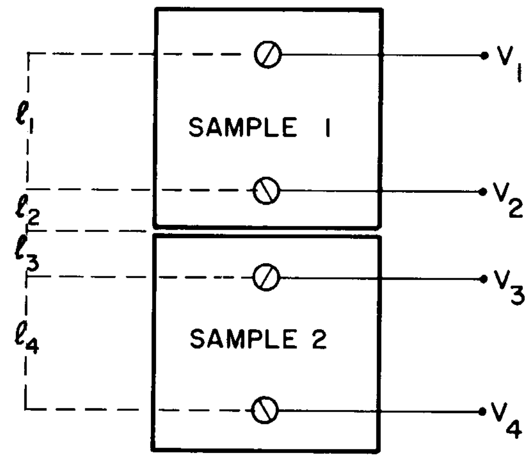


Figure 1 - Laboratory Apparatus for Measuring Interface Resistance



(a) Sample 1 = steel, Sample 2 = carbon, direct contact

$$\Delta V = V_2 - \left[V_3 + \left(\frac{V_4 - V_3}{\ell_4}\,\ell_3\right)\right]$$

(b) Sample 1 and 2 = steel, rodding mix between the two

$$\Delta V = \frac{V_3 - V_2}{2}$$

(c) Sample 1 and 2 = carbon, rodding mix between the two

$$\Delta V = \frac{\left[V_3 - \left(\frac{V_4 - V_3}{\ell_4}\right)\ell_3\right] - \left[V_2 + \left(\frac{V_2 - V_1}{\ell_1}\right)\ell_2\right]}{2}$$

and: $\boxed{R_c = \Delta V \frac{S}{I}}$

Where: ℓ = distance, mm

V = potential, volts

I = current, amperes

S = contact surface, mm^2

R_c = contact resistance, $ohm.mm^2$

Figure 2 - Method of Contact Resistance Calculation

Preparation of Rodding Mixes

Rodding mixes were prepared in the laboratory from calcined petroleum coke, commercial grade graphite and coal-tar pitch cut back with anthracene oil. The composition of the mixes is given in Table I.

From each rodding mix 38 mm diameter and 76 mm long specimens were prepared by pressing at 200 kg/cm^2 for shrinkage measurements. Linear shrinkage upon baking was measured in a dilatometer between 500 and 950°C.

Table I. Rodding Mix Formulations and Shrinkage Upon Baking

Mix:	A	B	C
Petroleum Coke			
Wt %:	36	53	35.5
Tyler mesh size:	-14 + 100	-4 + 200	-4 + 28
Graphite			
Wt %:	53	36	54
Tyler mesh size:	-48	-8	-4 + 200
Binder			
Wt %:	11	11	10.5
Pitch/Oil ratio:	1.8	2.1	2.0
Linear Shrinkage			
500 to 950°C, %:	0.42	0.16	0.05
Electric Resistivity			
at 850°C, μohm.m:	41.0	44.0	33.2

Contact Pressure Measurements

The pressure which develops between the steel stud and carbon anode during carbonization of the rodding mix was measured on a full size joint assembly. Commercial anodes 1400 mm long, 640 mm wide, and 500 mm high were cut in half transversally to obtain a carbon with one stud hole. The height was reduced to 320 mm. An air-tight, electrically heated furnace was built to accommodate the carbon rodded with a rectangular steel stud (AISI-1020 carbon steel) protruding 100 mm above the anode top.

Contact pressure was measured using a pneumatic metal chamber with direct gauge reading. Figure 3 shows the principle of the method. A thin, flexible chamber is placed between the carbon and steel stud. The chamber can be pressurized to maintain the vertical center plane of the stud in a permanent position while pressure is exerted on it from the rodding mix side during heating. The pneumatic chamber was constructed from 1.5 mm thick 304 stainless steel sheeting. Monitoring the position of the center plane of the stud was done with the aid of a dial gauge through quartz push rods. As the gauge indicated movement of the stud during heating the pressure in the chamber was adjusted to return the stud

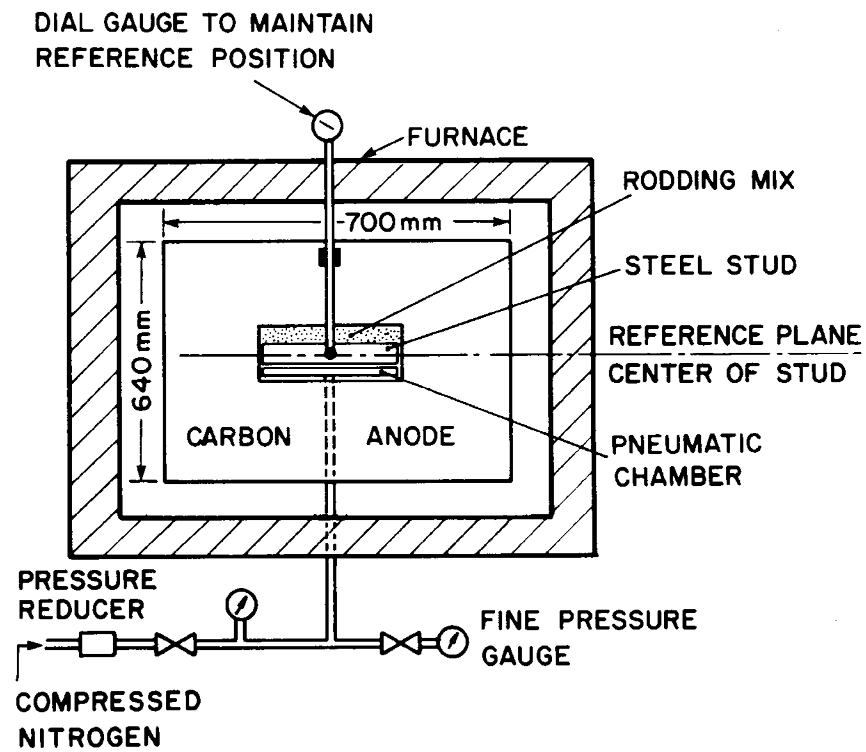


Figure 3 - Pneumatic Chamber Arrangement for Measuring Contact Pressure

From *Light Metals 1985*, H.O. Bohner, Editor

of its original position. The pressure readings were then plotted against temperature. The duration of a run was 5 days, readings being taken once every half hour.

The furnace could be heated to 900°C at a rate varying between 5 and 20°C/h. It was purged with nitrogen during the runs. The rodding procedure and heating profile selected were typical of those found in commercial practice. Figure 4 shows the heating rates adopted.

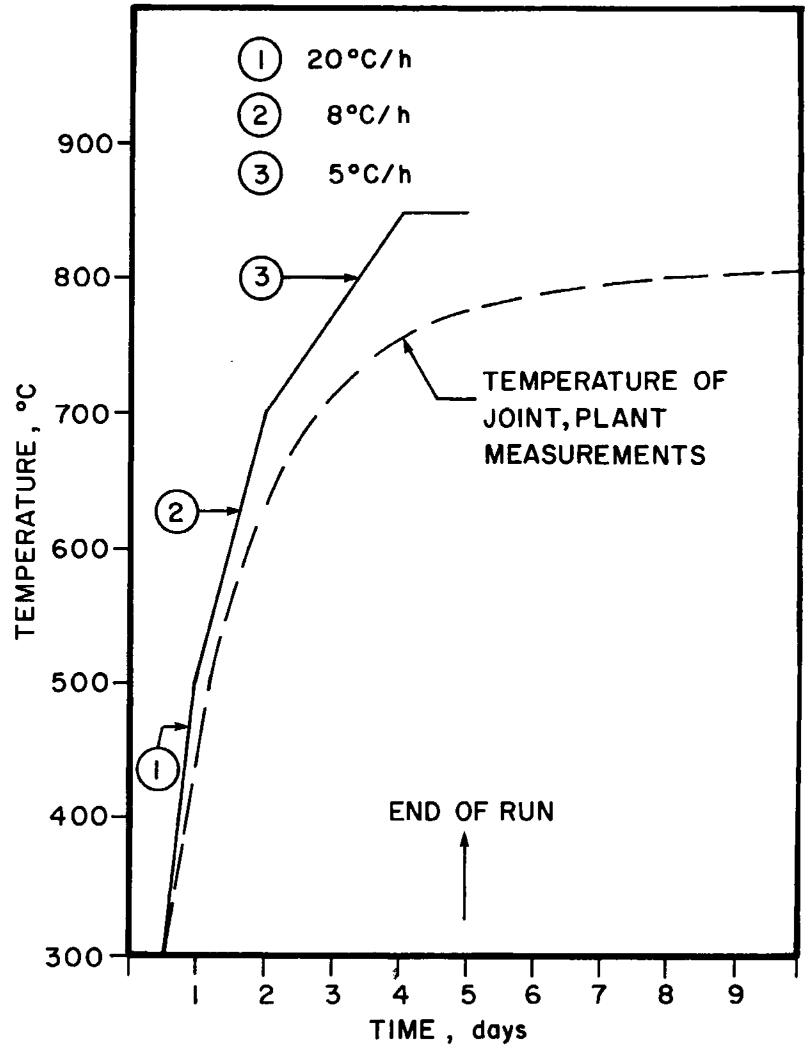


Figure 4 - Heating Rates Used in Contact Pressure Measurements

Results and Discussion

Steel-Carbon Contact Resistance

Contact resistance between mild steel and cores from prebaked anodes was measured in the laboratory apparatus between room temperature and 900°C at several contact pressures between 1 and 100 kg/cm^2. Figure 5 shows a typical plot of contact resistance results versus temperature at

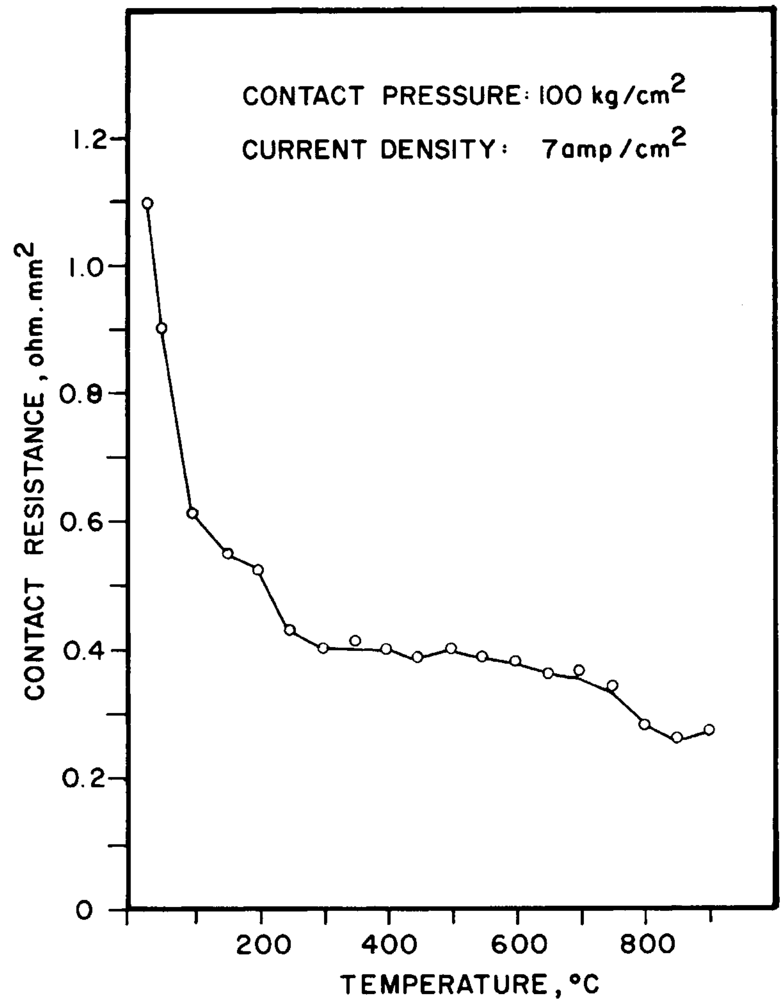


Figure 5 - Typical Contact Resistance vs Temperature Plot, Mild Steel to Carbon Anode Contact

100 kg/cm^2 contact pressure. The figure illustrates the frequency of readings and the scatter of results normally obtained. The precision of the measurement in terms of repeatability was found to be 0.05 ohm.mm^2.

Figure 6 shows contact resistance as a function of contact pressure for several temperatures. Each point is the mean of six measurements. The results are replotted in Figure 7 to illustrate the contact resistance - temperature correlation for selected contact pressures. Since the stud-carbon joint reaches about 450°C in the first day of anode life and its temperature stabilizes at around 800°C after about 6 days service (see Figure 4), only the experimental data obtained between 450 and 850°C have been used to construct the diagram in Figure 7. The effect of temperature

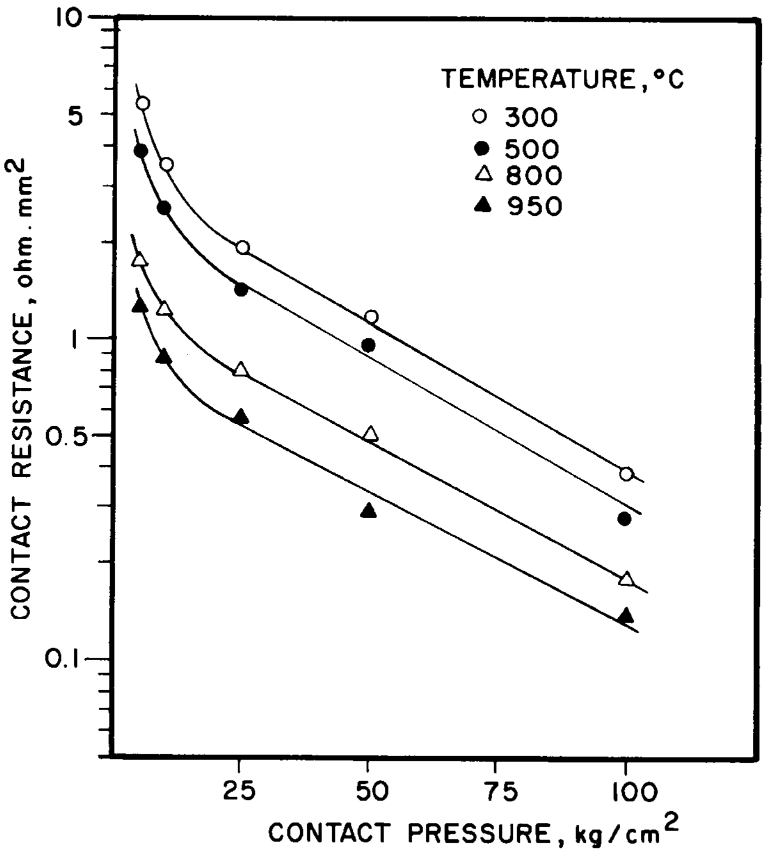


Figure 6 - Contact Resistance as a Function of Contact Pressure for Selected Temperatures

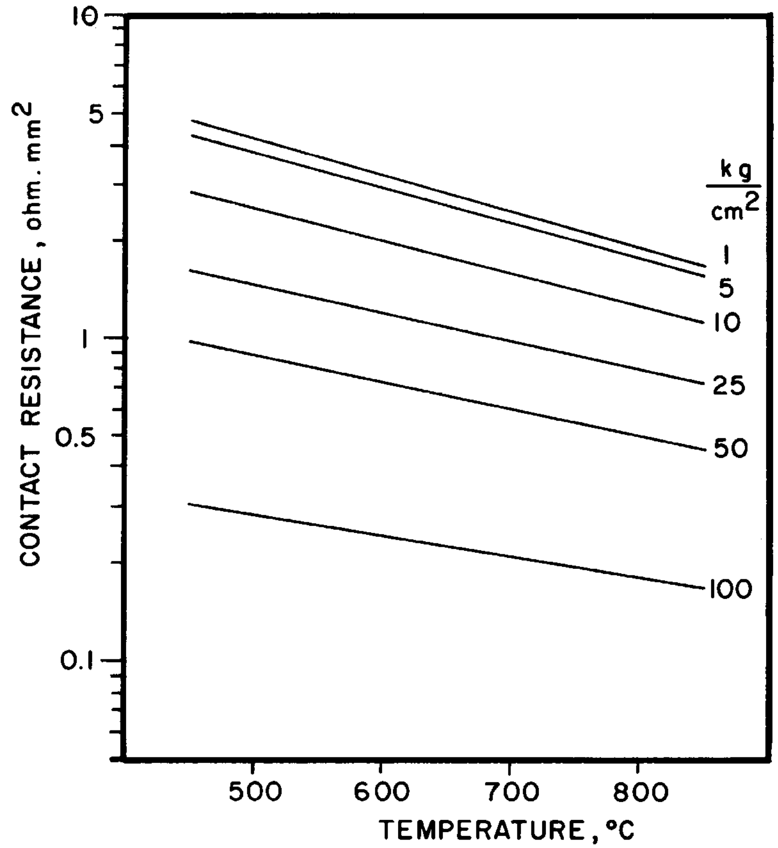


Figure 7 - Contact Resistance vs Temperature at various Contact Pressures

over this range is moderately small and is dependent on contact pressure. For example, at 5 kg/cm^2 pressure the decrease in contact resistance is 0.45 ohm.mm^2 when temperature increases from 700 to 800°C, while at 25 kg/cm^2 the corresponding decrease is 0.18 ohm.mm^2. As expected, the effect of contact pressure is highly significant. At 800°C contact resistance decreases by 0.95 ohm.mm^2 when contact pressure is increased from 5 to 25 kg/cm^2.

All measurements were done with new steel and carbon samples. To determine the effect of steel surface condition on contact resistance

Table II. Effect of Surface Condition and Reuse of Steel on Steel-Carbon Contact Resistance, ohm.mm^2, at 100 kg/cm^2 Contact Pressure

Steel Reused	Original Surface 500°C	Original Surface 800°C	Machined Surface 500°C	Machined Surface 800°C
new	0.28	0.10	0.38	0.18
1X	0.55	0.10	0.50	0.14
2X	0.88	0.40	0.38	0.18
3X	0.65	0.30	0.80	0.16
4X	0.82	0.25	0.56	0.18

steel samples with original and machined surface were reused in the measurements. The results are given in Table II. It can be seen that contact resistance at both 500°C and 800°C increases when the steel with original surface is reused. There is no statistically significant increase in contact resistance at either temperature in the case of machined surface.

It is an industrial practice to coat the stud with a carbonaceous paste to improve contact between steel and carbon. The effect of applying a 1 mm thick layer of graphite powder/anthracene oil paste to the steel on steel-carbon contact resistance was determined in the laboratory apparatus. The results given in Table III indicate favourable effect at

Table III. Effect of Surface Coating* of Steel on Steel-Carbon Contact Resistance, ohm.mm^2

Steel Reused, Coating	Pressure = 25 kg/cm^2 500°C	Pressure = 25 kg/cm^2 800°C	Pressure = 100 kg/cm^2 500°C	Pressure = 100 kg/cm^2 800°C
new, no coating	1.50	0.80	0.28	0.18
1X, coating	0.35	0.10	0.40	0.16
2X, coating	0.30	0.12	0.25	0.12
3X, coating	0.32	0.10	0.35	0.20
4X, coating	0.62	0.18	0.12	0.10
5X, coating	0.88	0.22	0.12	0.10

* graphite powder + anthracene oil, 50:50 by wt.

25 kg/cm^2 contact pressure. At 100 kg/cm^2 pressure there is no merit in using such coating. Similar results were obtained by using a paste prepared with graphite powder and synthetic resins.

Steel-Rodding Mix - Carbon Contact Resistance

Table IV summarizes the results obtained on rodding mix B with varying amounts of graphite content. It can be seen that mix-carbon contact resistance is slightly higher than steel-mix contact resistance. There is a definite beneficial effect on both when the graphite content of the rodding mix is increased. Contact resistance is significantly reduced by increasing the graphite content of the mix from the 40 wt% normally used to 80 wt%.

Table IV. Effect of Graphite Content in Rodding Mix on Steel-Mix and Mix-Carbon Contact Resistance, ohm.mm^2, at 25 kg/cm^2 Contact Pressure

Coke:Graphite wt. ratio	Steel - Mix 500°C	Steel - Mix 800°C	Mix - Carbon 500°C	Mix - Carbon 800°C
60:40	1.10	0.60	1.45	0.65
50:50	1.00	0.45	1.10	0.55
40:60	0.90	0.40	1.00	0.45
20:80	0.65	0.30	0.75	0.35

Contact Pressure Measurements

Figure 8 shows the result of contact pressure measurement using the pneumatic chamber and rodding mix C. Up to 500°C the mix absorbs the thermal expansion stress of the steel stud. Above this temperature when the mix has solidified contact pressure develops and reaches a maximum at 700 to 750°C. Due to phase transformation of steel, contact pressure decreases above 750°C and attains a minimum at 850°C. Somewhat lower contact pressures should be expected with mixes A and B which have higher shrinkage upon baking. Figure 9 compares the three mixes in terms of thermal strain calculated from measured thermal expansion values. It can be noted that the shape of the curves supports the load pattern obtained experimentally as shown in Figure 8.

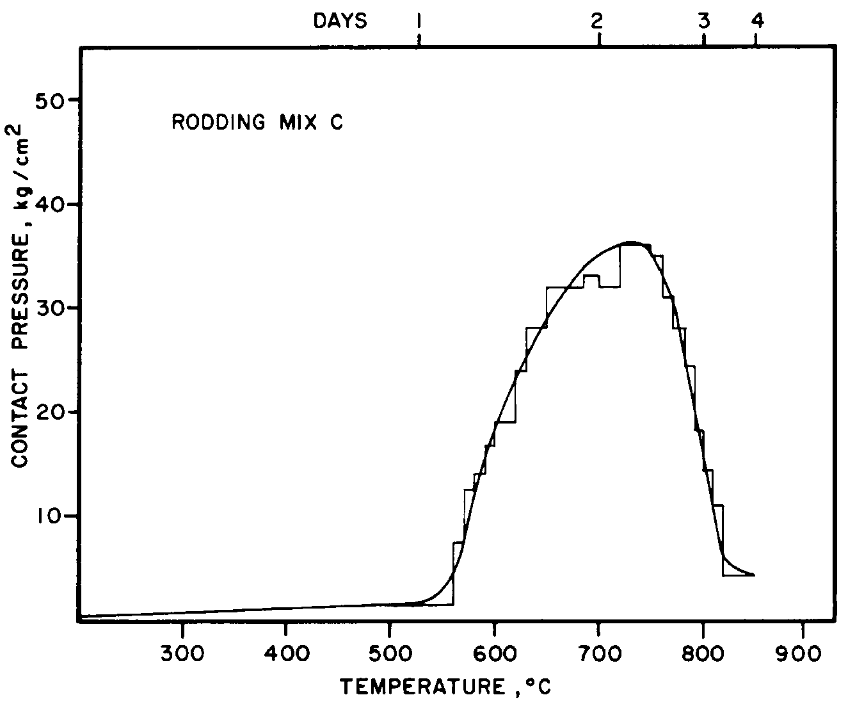


Figure 8 - Contact Pressure as a Function of Temperature

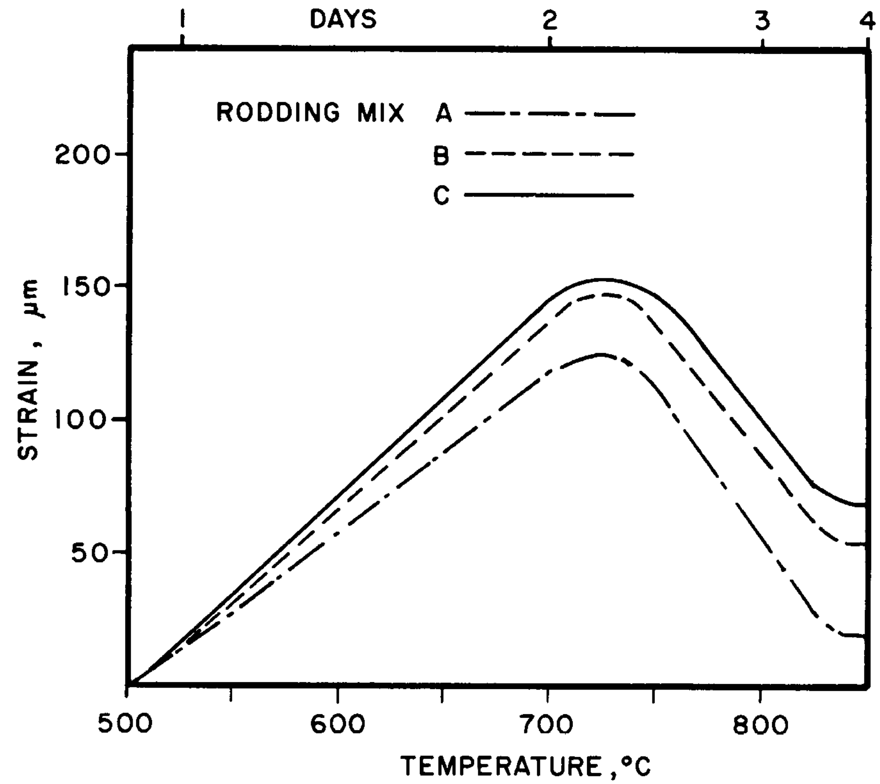


Figure 9 - Calculated Strain in Joint Due to Thermal Stresses.
(Stud: 280 mm × 62 mm × 100 mm deep,
Stud hole: 300 mm × 78 mm × 100 mm deep)

Figure 8 implies that during the first day after anode setting current pick-up takes place on the "dry" side of the joint. Bake-out and contact pressure development occur on the second day and final operating temperature for the joint is reached on the third and fourth day. Contact pressure from there on can be relatively low if joint temperature exceeds 850°C.

Interpretation of Results

From the equation given in Figure 2 it is seen that for a typical mix rodded rectangular stud drawing 3.2 kA current (Figure 10) a steel to carbon contact resistance of 0.1 $ohm.mm^2$ corresponds to 5.7 mV voltage drop:

$$V = R_c \frac{I}{S} = 0.1 \frac{3200}{56000} = 0.0057 \text{ volts}$$

Using this figure the experimental results can be interpreted as follows:

With the low-shrinkage rodding mix C after the first day of anode life when joint temperature reaches 600°C the contact voltage drop is expected to be in the vicinity of 80 mV. After the second day when temperature of the joint reaches 700 to 750°C voltage drop due to contact resistance attains minimum at around 40 mV. In the temperature region of steel phase transformation contact resistance should increase due to decreasing contact pressure. The predicted value from Figure 7 for temperatures in excess of 850°C is 85 mV. In reality this figure could be somewhat lower due to possible carburization reaction between steel and carbon which is expected to cause hysteresis in the contact pressure versus temperature relationship. It was found in the laboratory that contact resistance measured at 780°C and 10 kg/cm^2 decreases by 10 to 15% when the contact pressure is raised to 50 kg/cm^2 and lowered again to 10 kg/cm^2.

It is estimated that increasing the graphite content of the rodding mix aggregate from 40 to 80 wt.% reduces contact voltage drop by 20 to 30 mV at 600°C and by 18 mV at 800°C when contact pressure is near to 25 kg/cm^2. Coating the steel with a carbonaceous cement results in a reduction of 35 mV on the steel to carbon contact side of the joint at 800°C and 25 kg/cm^2 pressure.

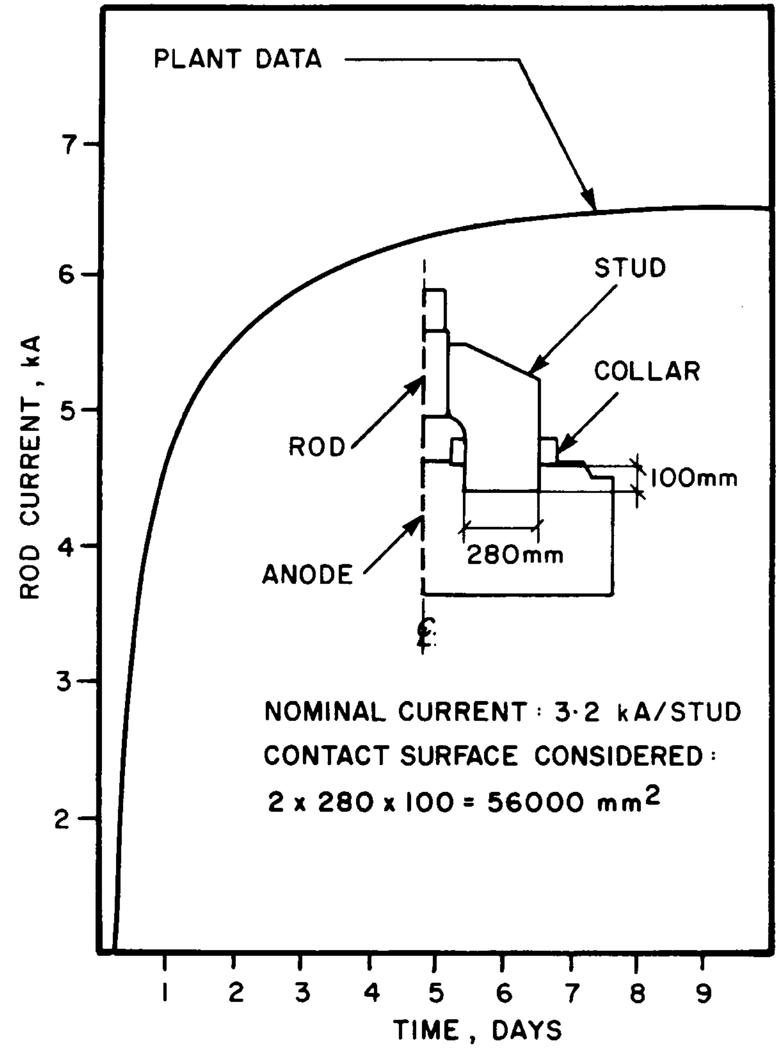


Figure 10 - Anode Rod Current Pick-up vs Time

Conclusions

Steel stud to carbon anode contact resistance can be reduced by decreasing the thermal shrinkage of the rodding mix, increasing the graphite content of the mix and applying a carbonaceous paste coating to the steel prior to rodding. Rodding mix with as low as 0.05% linear shrinkage can be made using a coarse graphite aggregate. It has been estimated that a total reduction of up to 50 mV in contact voltage drop is possible for a 280 mm wide and 100 mm deep mild steel to carbon anode joint at a current load of 3.2 kA by optimizing the rodding compounds.

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