Hot Roll Bonding of Steel

An investigation is carried out to determine the effects of temperature and deformation on the bonding of thin cold rolled steel with varied surface states

BY R. M. BRICK

SUMMARY. It is not possible by resistance solid state welding techniques to determine separately the effects of temperature and of deformation on the bonding of thin cold rolled low carbon steel plate having varied surface states. Therefore, experiments were devised where two strips of plate with varied surfaces were induction heated in 0.5 sec in a high vacuum to temperatures in the range of 1200 to 2000° F; the strips were then rolled together to deformations in the range from 5% to 35% reduction in thickness. The degree of bonding was judged qualitatively from interface microstructures. Results of the work include:

1. Microstructures have been correlated with bonding temperature, permitting a semi-quantitative "thumbprint" of solid state welding temperatures.
2. With only light air-formed oxide initially on the bond surface, even weak bonding requires a temperature where atomic mobility is sufficient to initiate recrystallization of moderately deformed steel, e.g. 1300° F.
3. Complete bonding, i.e., obliteration of the interface, requires a temperature of about 1800° F.
4. The presence of chromate-phosphate films, of chromium-chrome oxide films or of tin on one or both surfaces substantially raises the temperatures required for bonding, e.g.:

	Weak bond	*Good diffused bond*
Clean steel	1300°F	1800°F
Steel coating:		
CP	1700°F	2400°F
CCO	1600°F	2400°F
Tin	1900°F	2400°F

5. All of the above are based on deformations of about 20%. As expected, less deformation requires a higher temperature for bonding and vice versa.

Introduction

The objective of experiments reported in this paper was to determine the solid state bonding of two low carbon steel strips as a function of temperature, deformation of the steel and the texture or contaminant state of the bond surfaces. Furthermore, the experimental objective was to change these variables independently so as to isolate the effect of each. This is in contrast to the usual spot welding system where even for solid state bonding:

1. Change in surface state changes electrical resistivity and therefore the I^2Rt heating and resultant temperature attained.
2. Change in pressure changes resistivity, temperature and deformation (thinning) simultaneously.

Experimental Approach

Two $^1/_8$ in. wide strips of 6 mil thick cold rolled low carbon steel plate were tack welded together at points about 1 in. apart. The two facing surfaces in the intervening area, spaced with a gap of $^1/_8$ in. were prepared as desired, i.e. as to texture, coatings or contaminants. The specific surface conditions tested for bonding are given in Table 1.

The assembled strips were heated in $^1/_2$ sec to a temperature in the range from 1200° F (dark red color) up to 2600° F (approaching the melting point) and immediately passed between two hardened steel rolls. The gap at the pinch point of the rolls was controllably varied to get a desired deformation. The entire operation was carried out in a high vacuum to prevent oxidation of the steel surfaces. The equipment setup to accomplish this experiment is shown schematically in Fig. 1.

Heating of Strips

Direct induction heating was attempted using 20 kw, 450 kc power unit. None of the various induction coil shapes tried gave any temperature above a dull red heat even with times of several minutes. Then prior experience with ferrite magnetic flux concentrators led to the structure shown in Fig. 1. The ferrite flux units were in a 2 in. diameter, 2 in. high C-shape with a 3-turn induction coil around the center of the C. The section of the specimen to be heated was located in the open gap of the C.

The first experiments of this type were with the specimen rotated at 90° from the orientation shown by Fig. 1, i.e., the flat specimen faces were parallel to the faces of the gap opening. In this orientation, small spots of steel would melt and adjacent areas remain cold. However, when the specimen was rotated 90 deg. to the orientation shown by Fig. 1, heating was quite uniform over a 1 to $1^1/_2$ in. vertical distance. At any given power setting,

Table 1—Temperatures Measured with 3 Mil Iron-Constantan Thermocouples for Specimens Heated 0.5 Seconds at Indicated Power Settings and Quenched by Cold Roll Deformation

Power setting	Indicated temperature, °F	Microstructure (after rolling)
16	1150	Unrecrystallized cold worked structure.
17	1350	Moderately coarse recrystallized ferrite.
18	1450	Recrystallized ferrite plus trace of start of gamma formation at carbides.
20	1550	Recrystallized ferrite plus 10% f.g. ferrite from gamma.
22.5	1850	Fine grained normalized structure.
25	2100	Moderately coarse normalized grains.
35	2500[a]	Coarse grained structure.

[a] From chromel-alumel thermocouple tests.

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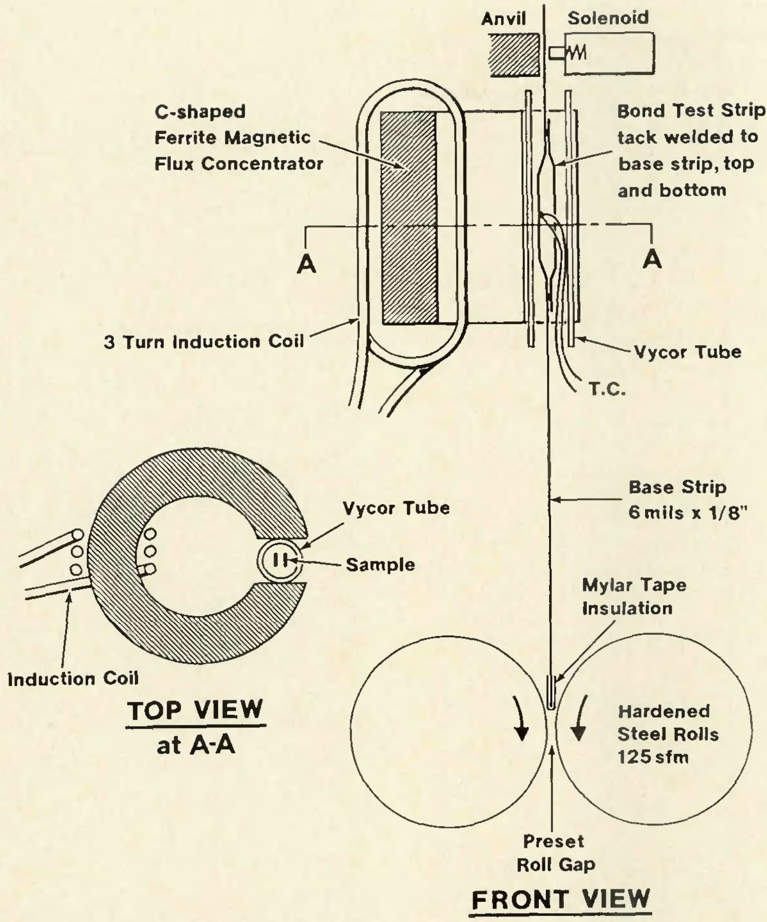

Fig. 1—Schematic diagram of roll-bonding apparatus

Table 2—Typical Deformations as a Function of Temperature

Roll gap, mils	Specimen temperature, °F	Final gauge[a], mils	Deformation, %
7.5	1200	10.2	18
7.5	1700	9.6	23
7.5	1900	9.0	27
7.5	2500	8.5	31
10.0	1700	11.4	8
10.0	1900	11.2	10
10.0	2400	10.9	12

[a] Initial gauge-12.2 mils

almost all heating occurred within 0.5 sec and prolonging the time beyond this had little effect. Therefore, in all bonding experiments, heating was for 0.5 sec, controlled by a timer.

Temperature was varied by changing the voltage input setting on the induction heating unit. For the 0.5 sec time, heating increased fairly uniformly from about 1000° F at a setting of 15 to about 2600° F at a setting of 35.

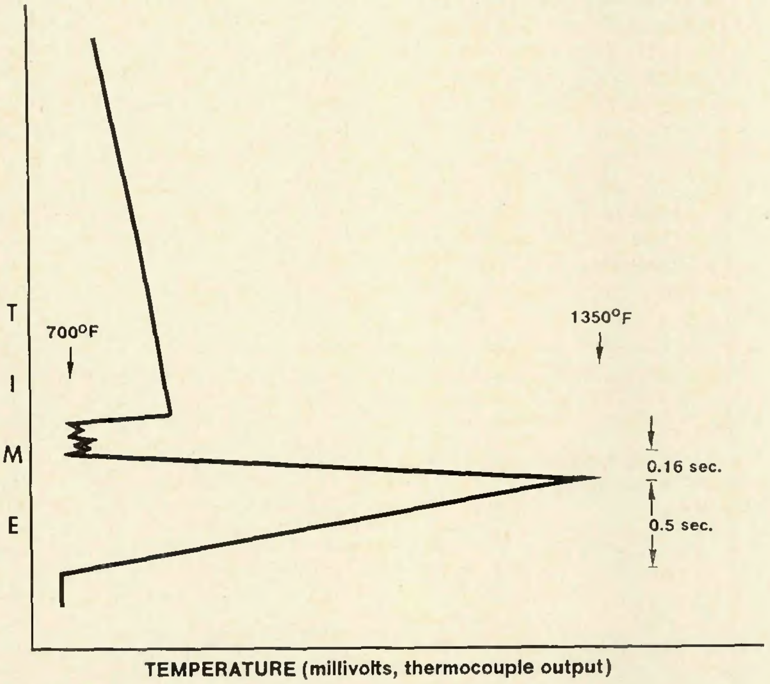

Fig. 2—Trace of 3 mil wire iron-constantan thermocouple response to heating of roll-bond specimen in 0.5 sec and dropping it through rotating cold rolls

It was found that the two steel strips to be bonded had to be separated about $^1/_8$ in. to heat effectively. However, this gap did not appear to be too critical because different specimens, prepared by hand rather than with any precisioning device, gave fairly good reproducibility of temperature. Thickness variation from 6 to 8 mils did not appear to have any significant effect on heating.

The specimens were held centered within the Vycor glass tube at the top by a spring loaded, solenoid-activated tip holding the strip (single thickness in this place) against an anvil. One of the two bond strips was long enough (Fig. 1) so that its bottom was just at the entrance of the roll gap, 6 in. below. This held the strips properly oriented at the bottom end and ensured entry of the heated 2-strip section into the roll pinch. In operation, the timer switch was so set up that when the power shut off after the 0.5 sec of heating, the solenoid at the top was automatically activated to release the strip. This dropped immediately, passing through the already rotating rolls.

Temperature Measurement

Bond temperatures were determined with 3 mil iron-constantan thermocouple wires, spot welded together and to one steel strip. Calibration runs were made using varied power settings as in Table 1. In each case, the specimen was heated in 0.5 sec and then dropped through the rolls, set to give a deformation of about 20%. The TC remained attached during the rolling and its output throughout the operation was recorded with a high speed XY recorder. A typical temperature-time chart is reproduced in Fig. 2. One roll-flattened thermocouple wire at the bond interface is shown in Fig. 3.

The very rapid temperature drop of Fig. 2 represents quenching of the specimen upon passing through and being slightly deformed by pressure of the cold steel rolls. Equivalent TC charts of specimens heated but not dropped—i.e., allowed to cool in vacuum—showed a temperature loss of about 60° F/sec, equivalent to about 10° F in the $^1/_6$ sec required to drop from the heating zone to the roll pinch.

Quenching of the heated strips by the rolls was an essential element since the temperature measurements were desired for a microstructural calibration. Without the quench by the rolls, the structure achieved at the maximum temperature was not sufficiently preserved to serve as a "fingerprint" record. Instead, it was obliterated by the normal steel structural changes occurring upon moderately slow cooling. However, having roll quenched the calibration specimens of Table 1 and observed the related microstructures, it was possible to use microstructures of all roll bonded specimens to estimate temperatures rather than have a thermocouple attached for each test.

Table 3—Experimental Data on Bonding of Steel in Vacuum of 0.07 Microns as a Function of Surface State, Deformation and Temperature

Specimen and surface	Deformation, %	Temperature, °F	Interface and bond
Low carbon cold rolled steel:			
Blackplate—degreased	16	800	No bond
	16	1150	No bond
	16	1250	Partial rex'l'd, weak bond
	17	1500	Bond line visible
	19	1750	Bond line visible
	23	2050	Diffused interface
	24	2200	Diffused interface
Blackplate—electropolished	14	1250	No bond
	15	1500 (Fig. 5)	Bond line visible
	21	2000	Diffused interface
	2	1250	No bond
	5	1550	Partially diffused interface
	6	1900	Diffused interface
	7	2400	Diffused interface
Blackplate—ground, 30 grit	18	1250	No bond
	18	1300 (Fig. 4)	Partial bond
	18	1350	Bond line visible
	18	1500	Bond line visible
	6	1250	No bond
	5	1500	Bond line visible
	9	1550	Bond line visible
	10	2100	Diffused interface
Parsivation Coated Surfaces:			
Blackplate vs CCO[a]	20	14500	No bond
	19	1600	Weak bond
	22	1800	Bond line visible
	23	1900	Bond line visible
	10	1850	No bond
	13	2100	Part diffused bond—Fig. 7
	14	2500	Diffused but visible—Fig. 8
CCO vs CCO[a]	4	1250	No bond
	7	1600	No bond
	9	2100	Bond line visible
	10	2300	Bond line visible
Blackplate vs TCR 210[b]	14	1250	No bond
	15	1450	No bond
	19	1700	Bond line visible
	19	1750	Bond line visible
	19	1800	Partial diffused bond—Fig. 6
	9	1850	No bond
	11	2100	Partial diffused bond
	14	2400	Diffused but visible
Tin Coated Surfaces:			
#25 Electrotin—75#/BB[c]	34	1250	No bond, wavy inter.
	34	1450	No bond
	34	1800	Bond, FeSn visible
	34	2100	Bond line visible
	22	1800	No bond
		2000	Bond line visible
		2300	Diffused bond
#25 Electrotin—55#/T8[d]	23	1600	No bond, FeSn visible
	27	2000	Junk in interface
	27	2100	Junk in interface
	11	1600	No bond
	15	2100	No bond
	15	2400	Diffused bond[e]—Fig. 9

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[a] 0.3 microinch of chromium plus 0.7 microinch of Cr_2O_3.

[b] Chromate-phosphate film about 1 microinch thick.

[c] Conventional (soft) temper, 8.2 mils thick; tin coating 15 microinch thick.

[d] Double cold reduced (35%), 6.0 mils thick; tin coating 15 microinch thick.

[e] Former interface etched bright, composition difference.

In the data of Table 3 the quoted temperatures are based on these microstructural observations. The temperature estimates are probably reliable to ±25° in the range 1300–1600°, ±50° in the range 1600–1900° F and ±75° above 2000°. The photomicrographs of Fig. 3–9 have been selected to show temperature effects on structure as well as bonding characteristics.

Roll Deformation Mechanism

Originally the $2^1/_4$ in. diameter rolls shown in Fig. 1 were cantilever suspended on 1 in. shafts going through a housing containing the gears that drove both rolls from a central motor-driven shaft. The housing was vacuum tight with O-ring seals where the shafts went through. This permitted the gears and drive to be at atmospheric pressure while the rolls were in vacuum.

The straightforward approach of cantilevered rolls did not prove to be satisfactory. There was enough elastic deflection of the shafts during rolling the 12.0 to 13.0 mils double thickness low carbon steel strips to cause the gap to become wedge shaped and roll the strip to a curve rather than a straight line. Therefore, an adjustable outboard yoke was employed to resist this deflection. While the yoke did not prevent elastic opening of the gap, it equalized it so that the roll faces remained parallel and deformation was uniform, resulting in a straight strip after hot rolling.

Rolls were made of hardened high speed tool steel. They rotated at a rate equivalent to a line speed of 125 fpm. Localized heat from deforming hot steel resulted in small transverse heat checks but these did not affect the experimental results.

Roll gap was varied simply by changing one of the pair of rolls to a roll of slightly larger or smaller diameter. Essentially all experiments were conducted with an initial roll gap of 7.5 mils or of 10.0 mils. These gave deformations in the range from 5% to 30%. Actual deformation was not constant for a given roll gap but varied directly with temperature. A higher temperature resulted in a softer

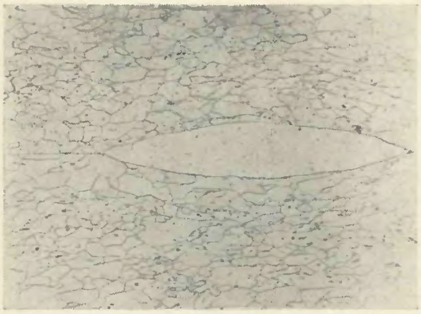

Fig. 3—Blackplate with 3 mil iron-constantan thermocouple attached to the inside surface of one strip, then roll bonded at 1400° F. The constantan wire, flattened to a lens shape by rolling, is visible at the bond interface in a recrystallized ferrite structure. X250 (reduced 46% on reproduction)

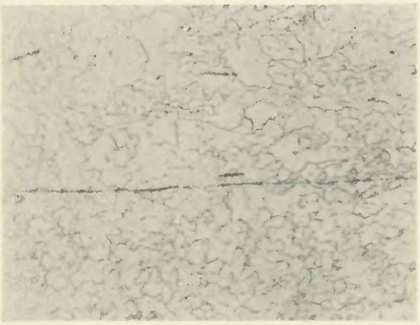

Fig. 6—Chromate-phosphate coated steel roll bonded to blackplate by 19% reduction at 1800° F. The chromate-phosphate film, disrupted at true bond spots on the interface, is evident in the fine grained normalized structure. (Note the film was also evident upon bonding at 2400° F but was less continuous.) X1000 (reduced 46% on reproduction)

steel, less resistance to deformation and therefore, less elastic spring of the roll housing and more deformation. Typical data appear in Table 2.

Vacuum System

The heating and rolling mechanisms were inside a vacuum bell jar mounted on a vacuum base plate with the center evacuation opening around which were 6 operational ports. The roll housing was mounted on one of these. Two were used for connecting the solenoid drop coil to the external power timer. Two were used to bring out the thermocouple wires to the XY recorder. The other one was used to bring out the water cooled copper induction coil tubes to the power supply. The vacuum system permitted pumping down to a vacuum of 0.07 microns in 20 minutes. Heating of specimens at this pressure gave no oxidation; they remained bright even upon heating to 2600° F. Therefore, all bonding experiments were conducted at this vacuum.

Experimental Results

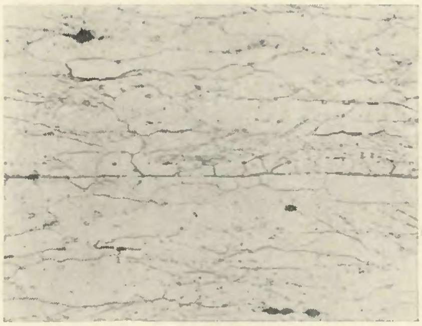

Fig. 4—Blackplate ground with 30 grit wheel and rolled 18% at about 1300° F. Original cold rolled structure unchanged except for recrystallization just at bond interface. X1000 (reduced 46% on reproduction)

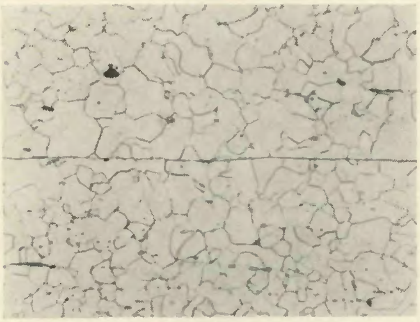

Fig. 7—CCO roll bonded to blackplate by 13% reduction at 1200° F. The chromium-chrome oxide film is visible at the interface in the moderate grain size normalized structure. X1000 (reduced 46% on reproduction)

Fig. 9—#25 electrolytic T-8 tinplate (15 microinch thick tin coating) roll bonded by 15 % reduction at about 2400° F. The coarse grained structure shows a completely diffused interface but a zone about ⅛ in. wide in the micrograph etched into the ferrite structure. X1000 (reduced 46% on reproduction)

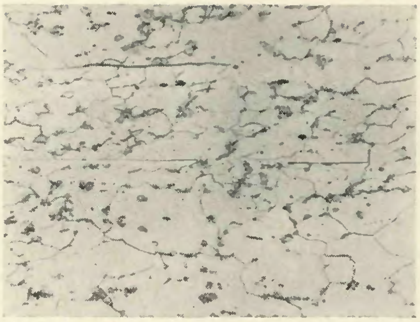

Fig. 5—Electropolished blackplate roll bonded by 15% deformation at about 1500° F. The bond interface is visible in a recrystallized ferrite matrix plus about 5% transformed austenite formed at carbide particle sites. X1000 (reduced 46% on reproduction)

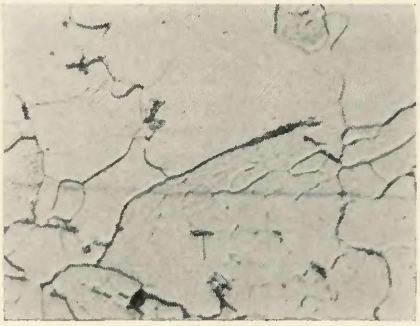

Fig. 8—CCO roll bonded to blackplate by 14% reduction at 2500° F. The CCO film has vanished in the very coarse grained structure. However, the original interface is visible in the completely diffused structure by an etching effect, here made visible by oblique lighting. Presumably both chromium and oxygen of the CCO diffused into the steel. X1000 (reduced 46% on reproduction)

For a given surface state, separate specimens were run at three or four power settings of the group 15, 20, 25, 30 and 35. A run was made starting at 20, then going up or down in power depending on whether or not bonding was observed. Subsequently, intermediate power settings were used to pinpoint more closely the minimum bonding temperature. After such a series with a roll gap of 7.5 mils, the testing was repeated with a roll gap of 10.0 mils. Using the thermocouple temperature—microstructure data of Table 1 with metallurgically based interpolations, microstructures of the roll bond-surface state test specimens were used to estimate the specimen roll bonding temperatures. The final data are given in Table 3.

Three caveats regarding these data should be made explicit, viz:

1. A "minimum" bond temperature for a given surface and deformation has not been defined. This would have required many more test runs at several power settings intermediate to those shown in Table 1.

2. The degree of bonding was not quantitatively established; specimens were evaluated initially on a "bond"—"no-bond" basis. However, the nature of the bond interface in metallographic sections (noted in Table 3) was indicative in that a "dirty" or "visible" interface would be a relatively weak bond while a diffused, invisible interface would be strong.

3. There is necessarily some uncertainty as to possible changes in the surfaces heated in vacuum prior to the roll bonding. However, the heating

curve of Fig. 2 indicates that the specimens were at the high temperature for only a small fraction of the 0.5 second total heat generation cycle.

Conclusions

1. *Plain Degreased Cold Rolled Steel.* The recrystallization temperature for low carbon steel cold rolled 35%, which is about 1350° F for the 0.5 sec heating cycle, must be reached or exceeded to obtain bonding, using a bonding deformation of about 17%. To obtain a good diffused bond with the original interface obliterated, the temperature must be 1800° F or higher.

2. *Texture Effects.* Comparison of the bonding of the as-rolled degreased black plate surfaces with very smooth electropolished surfaces (Fig. 5) or the roughened texture of surfaces ground with a 30 grit grinding wheel indicates: The data for 15 runs do not show that there was any significant effect of surface texture, with one exception. Two specimens of the 30 grit wheel ground specimens tested at a "low" temperature showed partial bonding with a structure not recrystallized except at the bond interface—Fig. 4. It is probable that these rough "hill-and-valley" surfaces under pressure were highly deformed locally and thus able to recrystallize whereas at that same temperature, the much less cold worked (35%) basic structure was below its recrystallization temperature. (*Note*: The same effect has been noted several times in spot welds of rough ground surfaces at low temperatures. Such bonds are weak but the observations support the hypothesis that atomic mobility sufficient to permit recrystallization is very useful and in general, even necessary to get a metallurgical bond.)

3. *Bonding of Passivation Coated Surfaces.* With a 1 microinch thick chromate-phosphate film on one bond surface, partial bonding in the sense that the surfaces stuck together but with no visible diffusion across the interface, required much more heat than black plate, i.e., close to 2100° F at a deformation of 11% or close to 1800° F at a deformation of 19%—Fig. 6. Even at 2400° F, approaching the melting point, the original interface was visible as lines, presumably of chromate-phosphate, but with areas of diffusion along these lines.

Steel with a chromium-chrome oxide film about 1 microinch thick on the surface appeared to be slightly more bondable, i.e., bonding was achieved at close to 1600° F at a deformation of 19% although the Cr-Cr_2O_3 film was visible even when bonded at 2100°—Fig. 7. The original interface was still visible at 2500° F, but in a different fashion. Instead of a broken line of particles at the bond interface, there was complete structural continuity, but the original interface etched as a bright line—Fig. 8. Probably the metallic chromium had dissolved in the ferrite resulting in a Cr-Fe diffusion alloy layer.

4. *Effect of Tin.* #25 electrotin plate, having a tin coating of 15 microinches on each bond surface, required:

(a) close to 2300° F for 15% deformation,

(b) close to 2000° F for 22 to 27% deformation, and

(c) close to 1800° F for 34% deformation.

In the last case, a line of alloy, FeSn, was present on the bond interface. A temperature of 2400° F resulted in the tin-alloyed ferrite readily visible as a zone 3 microns thick in Fig. 9.

Acknowledgement

All roll bonding experiments were carried out by R. Moessner.

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