Stress Relief Cracking in Pressure Vessel Steels

Stress relief cracking in A517F and A533A can be reduced by preheat and increased heat input

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ABSTRACT. In recent years a number of investigations have been undertaken both in the United States and abroad on the susceptibility of low alloy high strength steel weldments to cracking during stress relief. Results of these studies have indicated that cracking is related to the creep-rupture characteristics of the materials and may be considered a creep related phenomenon. They have indicated that microstructural processes occurring during the early stages of stress relief prevent creep deformation and promote grain boundary fracture. The fractures are most frequently found in the coarse grained heat-affected zone of weldments.

The investigation reported here is an attempt to examine three low alloy high strength steels of commonly used composition to determine their stress relief cracking behavior. The influence of base metal chemistry, of weld metal and base metal strength, and of welding heat input on the tendency to crack under constant restraint conditions was explored. Previous investigations have not included weld metal or base metal strength levels as a prime consideration nor have they included welding heat input as a part of their study.

Specimen blanks were prepared from A533-A, A517-F and A543 composition plate material. The blanks were heat treated to a variety of strength levels ranging from 78 ksi tensile strength to 165 ksi tensile strength and were welded with weld metals that ranged in tensile strength from 95 ksi to 165 ksi. The tests were made using 4 in. by 6 in. Lehigh restraint specimens prepared from the treated blanks. Welding heat inputs used were 22 kilojoules/in. and 48 kilojoules/in. No preheat was used with the 22 kilojoules/in. welds while 250° F preheat was used with the 48 kilojoules/in. welds.

The results of these tests showed that A517-F steel was sensitive to stress relief cracking in both the 22 and 48 kilojoules/in. tests; however, severe cracking occurred only in the 22 kilojoules/in. tests and under conditions of relatively high weld metal strength. High relative base metal strengths appear to suppress cracking and specimens welded at 48 kilojoules/in. showed only mild cracking tendencies. A533-A specimens showed only a moderate tendency toward stress relief cracking in the 22 kilojoules/in. tests and then only under conditions of high weld metal strength. Once again, high relative base metal strengths effectively suppressed the cracking. This steel was resistant to cracking in the 48 kilojoules/in. test. Because of the tendency to cold crack during the welding portion of the test, A543 steel was examined only using the 48 kilojoules/in. heat input. This steel showed no apparent cracking tendency in these tests.

As a result of this investigation, it may be concluded that the stress relief cracking tendency of low alloy high strength steels may be increased under conditions where relatively high weld metal strengths and low heat inputs are employed. Where lower strength weld metals are used and higher heat inputs applied, the cracking tendency will be substantially reduced.

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Introduction

Since the time the phenomenon was first reported in 1960,[1] a large number of investigations have been undertaken at Lehigh University[2, 3] and elsewhere to determine the nature and causes of stress relief cracking. Some of these investigations have proceeded along essentially parallel lines on three continents[4-6] with the results of the investigations being in relatively close agreement.

The sequence of events producing cracking is somewhat surprising to those unfamiliar with it. Sound crack-free weldments of susceptible steels are given a thermal stress relief treatment to reduce their residual stress level and to enhance their toughness. After thermal stress relief, usually in the range of 1000 to 1200° F, the weldments are found to be cracked, in some cases, cracked quite extensively. The cracks initiate at stress raisers—for example, at the toes of butt welds, and unfused roots of partial penetration welds and other geometrical discontinuities. They appear in the heat-affected zone of the welds in most cases, although weld metal cracking is not unknown.

Investigations[6, 7] have shown that the cracking is primarily intergranular in nature. The typical microstructural features which accompany and promote cracking are fine carbides precipitated within the grains of the heat-affected zone in combination with a denuded or a weakened grain boundary region. The creep strain normally accompanying thermal stress relief is forced into the weakened grain boundary region and the resulting extensive grain boundary deformation, usually accommodated by grain boundary sliding, produces intergranular cracks in the heat-affected zone. The presence of grain boundary carbides often observed in the susceptible steels serves to further restrict the amount of grain boundary deformation that can be accommodated without cracking. The weld heat-affected zone is particularly susceptible to cracking, because it has undergone a high temperature thermal cycle which serves to put many carbides into solution so that they subsequently reprecipitate during thermal stress relief.

In a recent survey[7] of stress relief cracking susceptibility in steels, a wide variety of low alloy steel compositions have been listed as strongly or moderately susceptible. Steels such as A517-B, D, E, F, J, A533-A, A542 and many others are included in this listing. As the result of a stress relief cracking study in Japan, Nakamura, et al.,[5] derived an equation which relates the chemical composition of steel to its susceptibility to stress relief cracking. This equation is:

$$\Delta G = [\mathrm{Cr}] + 3.3\,[\mathrm{Mo}] + 8.1\,[\mathrm{V}] - 2 \quad (1)$$

where ΔG is a crack susceptibility parameter and Cr, Mo, and V are concentrations in weight-percent of alloying elements present. When ΔG is equal to or greater than 0, the steel

Table 1—Chemical Compositions of the Steels, %

Steel	C	Mn	P	S	Si	Ni	Cr	Mo	Cu	V	B
A517-F heat 1	.16	.85	.013	.018	.20	.81	.58	.47	.24	.04	.002
A517-F heat 2	.18	.82	.010	.015	.22	.87	.58	.44	.30	.04	.004
A533-A	.19	1.24	.008	.019	.21	.08	.12	.44	.10	—	—
A543	.14	.30	.010	.018	.20	2.94	1.62	.42	.07	—	—

Table 2—As-Received Mechanical Properties of the Steels

	Yield strength, ksi	Tensile strength, ksi	Elongation in 2 in., %	Reduction of area, %
A517-F heat 1	114	127	20.0	63.0
A517-F heat 2	115	124	—	55.1
A533-A	61.9	80.3	25.0	—
A543	89.5	111	24.0	72.3

will exhibit stress relief cracking, provided the stress relief treatment is such that the mechanism for cracking is activated.

This potentially useful equation highlights the role of chromium, molybdenum and vanadium in the cracking phenomena. These three alloying elements contribute to cracking by promoting the precipitation of carbides during the stress relieving cycle. from eq (1) it may be seen that vanadium is considered to be the most significant of the three elements while chromium is of lesser importance.

It was one of the purposes of this investigation to experimentally verify the validity of the Nakamura equation by examining the stress relief cracking behavior of three low alloy high strength steels which contain some or all of these alloy elements. The three steels (A533-A, A517-F and A543) chosen for study in this investigation provide for a wide variation in ΔG from the Nakamura equation.

Of the various tests which have been employed to study stress relief cracking,[7] about half of these involve making actual weldments. Rarely in these investigations have the welding conditions been varied as a part of the experimental program. It was another purpose of this investigation to explore the role of welding parameters, principally welding heat input, on the extent of stress relief cracking under conditions of high restraint. The modified Lehigh restraint weldment specimen was used for the investigation because it permitted the variation in heat input necessary to investigate this parameter and because it had proven to be a reliable test of the stress relief cracking tendency of a variety of steels in previous investigations.

A third variable in this investigation was the relative weld metal and base metal strength of the steels tested. In previous investigations[3] it had been observed that some steels were more susceptible to cracking than others, but the strength levels at which the steels were examined were not always the same. Indeed, the usual condition of study was a steel at its normally used strength level and welded with an electrode of matching or slightly overmatching strength. While this provides a good measure of susceptibility with current industrial practices, it does not clearly define those conditions under which cracking might be most severe or under which cracking might be decreased. It was of interest, therefore, to examine how cracking tendency would vary when high strength base metal was matched to low strength weld metal or high strength weld metal matched to low strength base plate. From such an investigation, the extent of cracking that might be experienced under adverse conditions could be determined and some measure obtained of how much improvement in cracking tendency was possible as a result of correctly selecting the weld metal and base plate strengths.

Experimental Procedure

Materials

The as-received mechanical properties and compositions of the three steels chosen for investigation, A533-A, A517-F and A543, are found in Tables 1 and 2. The A533-A material was received in the normalized and stress relieved condition, while the

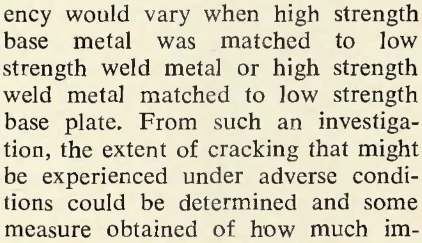

Fig. 2—Two dimensional view of typical stress relief cracks in Lehigh restraint specimens. Left—A517 Grade F steel; right—A542 steel

LEHIGH RESTRAINT SPECIMEN

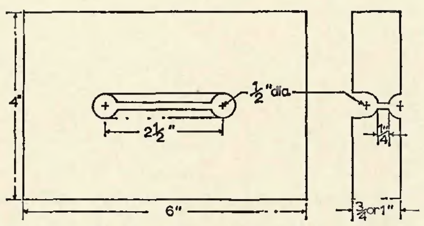

Fig. 1.—The Lehigh restraint specimen

A517-F and the A543 were received in the quenched and tempered condition. In order to vary the strength levels of these three materials, they were heat treated by quenching and tempering at various temperatures. Therefore, all of the specimens investigated in this program were tested in the quenched and tempered condition.

The procedure used to prepare the specimens was to austenitize them at 1650° F (1700° F for A517-F) in the form of 6 in. x 9 in. specimen blanks and to quench them in brine. The various strength levels required were then obtained by tempering the specimen blanks at the appropriate temperatures and time. The A517-F material was tested in two heats of different thickness—¾ in. and 1 in.—while the A533-A and the A543 were tested in the ¾ in. thickness only.

Because some of the strength levels used for the base metal do not meet the ASTM specifications for the various grades, it is really proper to refer to them in some cases as A517-F, A533-A, and A543 *composition* materials only. For simplicity they will be referred to by their ASTM designation, however, the strength levels should also be noted.

Specimen

The specimen used to investigate stress relief cracking was the modified Lehigh restraint specimen seen in Fig. 1. This specimen had been used in previous investigations[2, 3, 6] of stress relief cracking and had proven to be a reliable indicator of cracking tendency. The Lehigh restraint specimen was originally developed as a test for cold cracking, although hot cracking of weld metal may also be revealed in this test. Hot cracking in the heat-affected zone is not usually revealed in this test, and this makes the test readily amenable to stress relief cracking studies because such cracking usually occurs in the heat affected zone also.

The test will also reveal cold cracking, and this must be differentiated from subsequent stress relief cracks. The specific metallographic appearance of the stress relief cracks in the heat-affected zone are one means of identifying cold cracking from stress relief cracking. Cold cracking may, in some instances, follow the prior austenite grain boundaries; however, it more often follows martensite plate boundaries. Stress relief cracking in these steels is exclusively intergranular in the coarse grained heat-affected zone. The typical appearance of stress relief cracks may be seen in Fig. 2. The cracks are shown on two planes, along their length and transverse to their length.

Two heat inputs were used to weld the specimens. The first was a low heat input and no preheat was applied prior to welding. The parameters were 200 amp, 20-24 v and a travel speed of approximately 11 ipm. This resulted in a heat input of 20-24 kilojoules/in. For convenience, this will be referred to as the 22 kilojoules/in. condition.

A second welding condition involving a higher heat input and preheat was also utilized. The welding parameters for this condition were 200 amp 20-24 v and a travel speed of approximately 5½ ipm. This resulted in a heat input of 45-50 kilojoules/in. A preheat of 250° F was applied prior to welding.

In order to produce welds of varying strengths, a variety of shielded metal arc electrodes were used. Since the cracking during stress relief was confined completely to the base metal heat-affected zone, the chemical compositions of the electrodes used were not determined—rather they were selected on the basis of the strength level that they would provide for each welded combination.

The electrodes used in the investigation were of the low hydrogen type to minimize cold cracking and were the following: E7016, E7018, E8018, E10016, E11018, and E13018. All electrodes were $^1/_4$ in. or $^5/_{16}$ in. in diameter. The welds in the investigation were made with an automatic shielded metal arc welding machine. Because of the tendency of the A543 and the A533-A to cold crack on welding, a postweld treatment of 250° F for 2 hr was applied to A533-A after extensive cracking occurred in some specimens.

Testing Procedure

After the materials had been heat

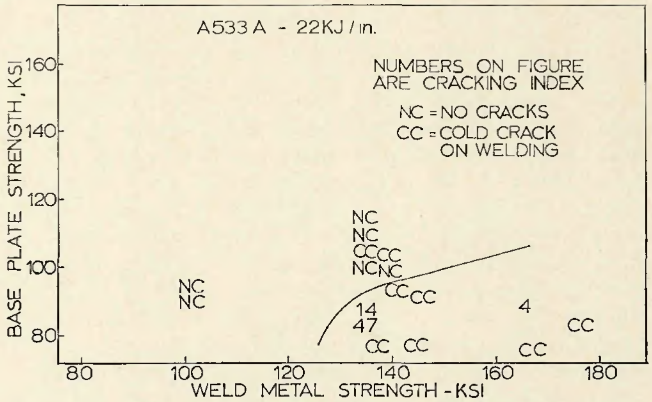

Fig. 5—The influence of weld metal and base metal strength on stress relief cracking in A533A welded at low heat input

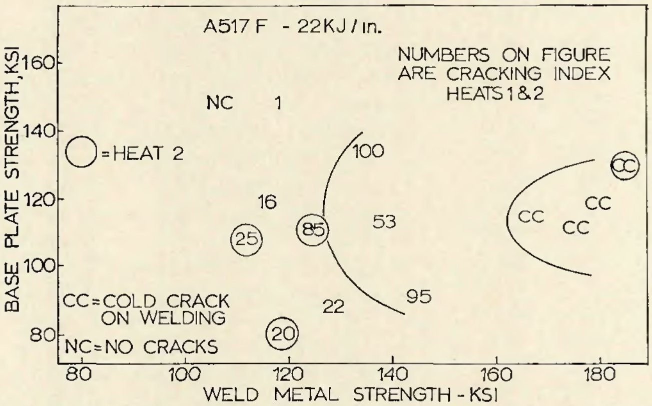

Fig. 3—The influence of weld metal and base metal strength on stress relief cracking in A517F welded at low heat input

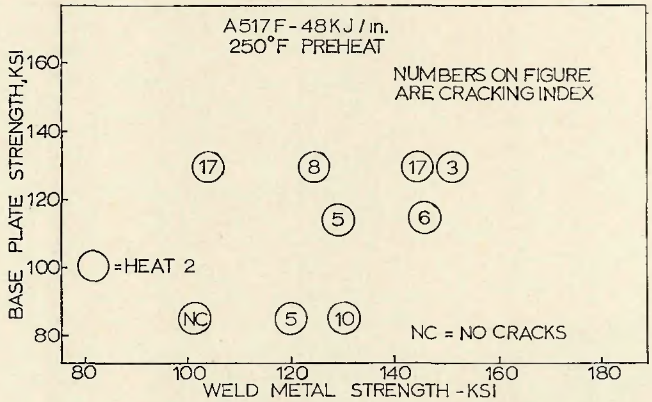

Fig. 4—The influence of weld metal and base metal strength on stress relief cracking in A517F welded at high heat input

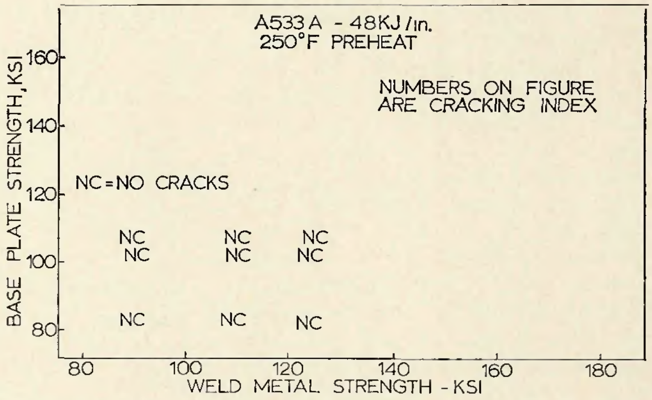

Fig. 6—The influence of weld metal and base metal strength on stress relief cracking in A533-A welded at high heat input

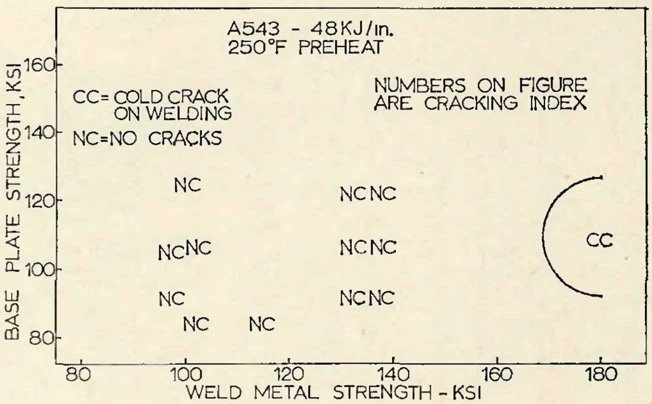

Fig. 7 (right)—The influence of weld metal and base metal strength on stress relief cracking in A543 welded at high heat input treated in the form of 6 in. x 9 in. specimen blanks, the groove was machined in the specimen and they were welded using one of the two welding conditions indicated above. The strength levels of the plate materials varied, and the welding electrodes were matched to them in such a way that in some cases the weld metal was matching to the base metal; in some cases it overmatched the base metal; and in other cases it undermatched the base metal. The weld metal and base metal strengths achieved are indicated on Figs. 3-7. The tensile strengths indicated are based on hardness tests made on the stress relieved weldments; the tensile strength of the weld deposits are based on Rockwell hardness tests while the tensile strength of the base metal materials are based on Brinell hardness tests.

After welding, the specimens were placed in a cold stress relieving furnace and heated with the furnace to a stress relief temperature of 1100-1150° F. They were held in the furnace for a period of 19 hr and then were air cooled from the stress relief temperature. The air cooled specimens were sectioned in such a way that the two halves of the specimen were attached solely by the weld metal—that is, the two ends of the specimen were cut through the holes shown in Fig. 1.

The specimen was cooled to the temperature of liquid nitrogen and one side of the specimen was placed in a vise. The other side of the specimen was struck with a hammer so that it fractured through the weld area. The fracture naturally sought out any cracks that were present in the weld metal or heat-affected zone. Cracks present prior to or forming during stress relief were discolored (oxidized) from the stress relief treatment and these cracks were clearly distinguishable from the crack produced by the fracturing in the vise. Since the fracture tended to follow the crack path, the full extent of cracking present, not only its depth but also its length and geometrical configuration, could be seen in the weldment.

In order to effectively rate these cracks, a cracking index was employed. This cracking index is a measure of the crack cross sectional area compared to the cross sectional area of the weldment at that point. This was done by projecting the area of the crack on a plane perpendicular to the weldment at the center of the weld. Thus, a weldment showing a stress relief cracking index number of 15 had a crack whose projected cross-sectional area was approximately 15% of the cross-sectional area of the weldment down the center line of the weld.

The stress relief cracks were found entirely in the heat-affected zone and were curved; thus the actual area of these cracks was somewhat larger than indicated by the index. In several instances metallography of the cracked specimen was undertaken to ensure that the cracks examined were stress relieved cracks rather than cold cracks as a result of the welding. Cold cracking, when it did appear, was exclusively limited to center cracks in the weld metal. These cracks were readily apparent when they occurred, usually right after welding. The tests which did show cold cracking are indicated on the figures. The tensile strengths for these specimens shown on the figures are for the *as-welded* condition since stress relief of these specimens was not meaningful when cracking had already relieved the stresses present.

Results and Discussion

The results of the stress relief cracking tests using the modified Lehigh restraint specimen are seen in Fig. 3-7. Figures 3 and 4 show the results of the low and high heat input tests on A517-F, respectively. Figures 5 and 6 show the results of the low and high heat input tests on A533-A, respectively, and Fig. 7 shows the results of the high heat input tests on A543. For both A533-A and A543, it was difficult to make low heat input weldments without extensive cold cracking. Even with the A517-F material, low heat input tests with high weld metal strength levels regularly produced some cold cracking and this is indicated on Fig. 3. Because the cold cracking tendency for the A533-A material was quite strong, the mild postheat treatment of 250° F for 2 hr was applied to the A533-A specimens after some initial tests had cold cracked.

Examination of Fig. 3-7 provides a rather clear picture of some of the factors which influence stress relief cracking. It should first be noted that the A517-F steel is quite sensitive to stress relief cracking. This is generally in agreement with the equation developed by Nakamura—eq (1)—in that the two heats of A517-F studied here gave a ΔG of +0.45 and +0.35 for heats 1 and 2, respectively.

Similarly, the A533-A steel which had a ΔG of -0.43 showed much less tendency to stress relief crack. It should be noted, however, that this steel did show some cracking tendency, especially when welded at a low heat input and without preheat, which maximized the cracking for the A517-F. It is clear, however, since there is also a strong cold cracking tendency, welding without preheat is not very feasible for this steel. The stress relief cracking tendency has been reported by others for this steel[7] but would not be predicted by eq (1).

The A543 steel on the other hand, which should have been crack sensitive according to the Nakamura equation, having a ΔG +1.03, did not show any cracking. It appears that other chemical and microstructural features not included in this equation are significant in promoting or reducing cracking tendency during stress relief.

It may also be observed from these figures that the conditions which maximized cracking are those which couple a weak base metal with a strong weld metal. This should not be surprising, because we might imagine that under these conditions the weld metal will not yield appreciably nor creep during stress relief. Stress relief must then occur by plastic flow of the base metal or heat-affected zone material. If plastic deformation is required of the heat-affected zone and a tendency for stress relief cracking is present, this tendency will be accentuated. On the other hand, under conditions where the base metal and heat-affected zone are strong and the weld metal relatively weak, the weld metal will undergo plastic deformation during the stress relief process in preference to the heat-affected zone. Under these conditions the limited deformation required of the heat-affected zone will decrease its susceptibility to stress relief cracking.

This observation may not always be a useful one. For A517-F welded at the low heat input, the only conditions which produced small amounts of stress relief cracking were those in which very high base metal strengths were employed in conjunction with rather weak weld metals. Such a combination is not a practical one for this material. Of much greater usefulness is the information obtained from the tests run at different heat inputs.

Increasing the heat input (and preheat) appears to substantially decrease the tendency for stress relief cracking in the A517-F and A533-A materials. As may be clearly seen from Fig. 3, although cracking indices of 100 were experienced in A517-F welded at 22 kilojoules/in., the higher heat input tests—Fig. 4—produced cracking indices which did not exceed 20. Thus, the cracking was to a large extent controlled by preheat and higher heat inputs. For A533-A—Fig. 6—stress relief cracking was effectively eliminated by the use of the preheat and higher heat input, as was the cold cracking.

These results could be rationalized on the basis of reduced restraint in the higher heat input tests arising from the fact that the weld bead is larger and thicker and therefore the restraint stress in the weldment heat-affected zone will be reduced. However, measurement of the actual weld beads for the high and low heat input tests do not show a marked difference and a reduction in stress appears unlikely.

An alternate explanation for this behavior may be made on the basis of the thermal cycle in the weld heat-affected zone. The higher heat input welds produce a softer heat-affected zone because of a slower cooling rate from the weld thermal cycle. This produces a zone which is better able to accommodate creep strains without requiring extensive grain boundary deformation because deformation is more uniformly distributed within the grains of the heat-affected zone. Grain boundary sliding, and thus stress relief cracking, is reduced.

Another factor also of significance but more difficult to ascertain was the actual characteristics of the weld metal and heat-affected zone during the stress relieving cycle. It might be anticipated that weld metals which temper rapidly during the stress relieving cycle may reduce the susceptibility of the weldment to cracking, while those that retain their strength during this cycle may force more extensive plastic deformation in the heat-affected zone and thus promote cracking.

During this study, with the exception of the cold cracked welds, only the weld metal strengths after stress relief were measured and thus the actual characteristics of the weld metal during the stress relief were not considered as a part of the program. In spite of this limitation, the relatively uniform data produced by the variety of weld metals studied appears to indicate that this factor may not be as important as might otherwise be assumed. This may be particularly true because stress relief cracking may occur primarily during the heating portion of the cycle and the initial period of stress relief. If this is the case, and it has been demonstrated in several investigations that it apparently is,[2] then tempering characteristics of the weld metals at low temperatures may not be sufficiently different to cause their long time or overall tempering characteristics to have much influence. That is, stress relief cracking may occur below 1100° F, in a temperature range where softening due to tempering is insignificant.

Conclusions

From this investigation, the following may be concluded:

1. Of the 3 steels examined for potential for stress relief cracking, two of these steels, A533-A and A517-F do show stress relief cracking in laboratory tests. A517-F showed the most extensive cracking, while A543 did not stress relief crack.

2. The equation developed by Nakamura, et al., which predicts stress relief cracking tendency on the basis of base metal chemistry:

$$\Delta G = [\mathrm{Cr}] + 3.3\,[\mathrm{Mo}] + 8.1\,[\mathrm{V}] - 2$$

did not rate the steels in the correct order of their true cracking susceptibility, nor did it predict that the A533-A steel would crack during stress relief. Thus it appears that this equation does not fit all of the conditions applicable to low alloy steels.

3. The conditions which promote cracking are high weld metal strength in conjunction with lower base metal strength. High base metal strength in conjunction with lower weld metal strength appears to decrease the cracking tendency. Welds in A533-A which had matching weld metal-base metal strengths did not produce stress relief cracking. Matching weld metal-base metal strengths in the A517-F steel did produce cracking.

4. Heat input appears to influence the extent of stress relief cracking. Welds made at the 22 kilojoules/in. with no preheat produce extensive cracking in A517-F and mild cracking in A543-A. Welds made at 48 kilojoules/in. using a 250° F preheat produced no cracking in A533-A and only slight cracking in A517-F. Thus higher heat input appears to decrease the cracking tendency in these two steels.

Acknowledgements

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