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SOME EFFECTS OF SURFACE CONDITION ON THE STRESS CORROSION CRACKING OF LINE PIPE STEEL

J. A. Beavers and T. K. Christman
Battelle's Columbus Division
505 King Avenue
Columbus, Ohio 43201

R. N. Parkins
Department of Metallurgy
University of Newcastle upon Tyne
Newcastle upon Tyne, England NE1 7RU

INTRODUCTION

The Pipeline Research Committee of the American Gas Association has funded a number of research programs at Battelle's Columbus Division and the University of Newcastle on stress-corrosion cracking (SCC) of line pipe steels since the first reported field failures in the mid 1960's. The primary objective of the research has been to identify the root cause of the failures and identify practicable mitigation procedures. One aspect of the research that has received considerable attention in recent years has been the relationship between surface properties of the line pipe steels and SCC susceptibility. In this paper, the recent findings in this area are summarized.

BACKGROUND

The first reported external SCC failure of a natural gas pipeline occurred in 1965[1] and subsequently, a number of similar failures have occurred. Most of these failures have had a number of similar features.[1,2]

- Cracking is intergranular and branching.
- The leak or rupture occurs as a result of link-up of numerous cracks.
- A black film, consisting of $FeCO_3$ and Fe_3O_4 is normally found on the intergranular fracture surfaces.
- Most failures occur within 10 miles of the discharge side of the compressor station.
- Most SCC failures have occurred with coated pipe.
- All failures have occurred on cathodically protected pipe.
- Most failures occur on normal wrought line pipe but occasional failure has been associated with stress raisers, such as dents or near the welds.

Results of laboratory and field studies[1-4] have demonstrated that the root cause of the failure is a carbonate-bicarbonate solution which develops at the pipe surface as a result of the applied cathodic protection (CP). Where the levels of CP are inadequate or where the pipe surface is shielded from the CP, the potential may be in the cracking range.[5] Thus, the applied CP not only generates the cracking environment, it also may hold the pipe-to-soil potential in the cracking range. The proximity of most of the failures to the compressor station is a consequence of the high temperature in this region; cracking velocities have been shown to follow Arrhenius behavior.[6,7]

SURFACE FACTORS AFFECTING SCC SUSCEPTIBILITY

A number of surface related factors have been identified which are thought to influence SCC susceptibility. These include the presence of mill scale, surface pitting, near surface compositional changes, residual stress and finally, the near-surface stress state.

Role of Mill Scale

It is well established that seasoned (exposed to an underground environment) mill scaled surfaces on line pipe steels are more susceptible to SCC than are machined surfaces. Typical threshold stress data for machined and mill scaled surfaces of an X-52 steel that failed in service are given in Figure 1.[8] The root cause for this increased susceptibility is not known but it has been speculated that the mill scale plays a detrimental role. However, results of recent studies have shown, at least for one steel, an inverse relationship between surface coverage with mill scale and SCC susceptibility, see Figure 2. This behavior is thought to occur as a result of the protective nature of the mill scale which prevents access of the cracking environment to the surface, and the absence of pits beneath the mill scale. Thus, most of the cracks in the specimens occurred at the base of pits where gaps in the mill scale were present.

The above SCC studies were performed under potential control and thus any detrimental effect that the mill scale may have on the electrochemical potential is not expressed. On the other hand, results of experiments performed with artificial crevices on mill scaled and machined surfaces have shown that the presence of the mill scale tends to hold the electrochemical potential within the cracking range.[9] Typical data demonstrating this effect are given in Figure 3. Thus, the overriding effect of mill scale on an operating pipeline is probably detrimental because of its detrimental potential behavior and because a continuous mill scale cannot be guaranteed. Mill scale will tend to promote pitting on adjacent non mill scaled areas.

Role of Surface Pitting

The role of surface pitting on SCC and its relationship to mill scale was alluded to in the previous section. Thus, for one steel, an inverse correlation was found between mill scale coverage and pit density, as shown in Figure 4. Not surprisingly, a good correlation also was found between pit density and SCC as shown in Figure 5.

In order to further investigate the role of pitting on SCC susceptibility, machined, and seasoned surfaces of specimens of two steels were exposed to an ASTM salt spray test (ASTM B117) for two weeks prior to performing the standardized SCC susceptibility test in 1N $NaHCO_3$-1N Na_2CO_3 at 75 C. This salt spray exposure produces pitting on the machine surfaces which is similar in morphology to the pitting normally encountered on seasoned pipe surfaces after a number of years of exposure to an underground environment.

Results of the experiments for two steels, given in Figures 6 and 7, show that the threshold stress for SCC of machined surfaces on one steel, X-52T, dropped to values measured for seasoned surfaces of that steel as a result of surface rusting. Thus, for this particular steel, it appears that pitting produced by salt spray exposure is sufficient to greatly increase cracking susceptibility. On the other hand, surface rusting of a second more SCC resistant steel (X-52B) produced only a small decrease in the threshold stress. The mill scale surface of this steel had not been exposed to a service environment and thus had relatively less pitting than the seasoned surfaces of the X-52T specimens but, nevertheless, neither the mill scaled nor the machined surfaces were particularly sensitive to the surface rusting.

In separate mechanical tests, the susceptible steel (X-52T) underwent plastic deformation at stresses well below the 0.5 percent total strain yield strength whereas the resistant steel (X-52B) exhibited elastic stress-strain behavior up to the upper yield point. Based on these observations, it has been speculated that a synergistic interaction between surface pits and mechanical behavior affects SCC susceptibility by means of their influence on surface plastic deformation. This hypothesis is being investigated through SCC tests being performed on specimens containing electrochemically machined notches of varying stress concentration.

Decarburization

It is well established that low carbon steels are more susceptible to anodic SCC than steels having carbon contents that are typical of C-Mn line pipe steels, about 0.2 C.[10] Thus, one might speculate that specimens having decarburized surfaces would tend to exhibit increased susceptibility to SCC and laboratory results tend to confirm this behavior, see Figure 8.[11]

On the other hand, results of a recent study[8] suggest that decarburization may not play a significant role in affecting the SCC susceptibility of actual line pipe steels. Decarburization layer thicknesses were measured metallographically in specimens of three line pipe steels that exhibited considerable specimen-to-specimen and material-to-material variability in SCC susceptibility. There was no evidence of decarburization in any of the three steels, even though two of the three steels had significant mill scale coverage and had not been exposed to an underground environment; for the third steel it could be speculated that any decarburization layer present was consumed as a result of exposure to the underground environment.

Surface Residual Stresses

The role of surface residual stresses on SCC susceptibility of actual pipelines has not been established but it can be speculated that cracking is affected. Most ring sections removed from operating pipelines open upon longitudinal splitting, indicating the presence of tensile residual stresses in the pipe. Analysis of a number of rings from operating pipelines indicate that these stresses may be as high as 87 percent of specified minimum yield strength (SMYS).[12] It is also probable that the residual stresses vary around the circumference of the pipe and this variation may be responsible for some of the variability observed in threshold stress data for a given line pipe steel. A study of the possible range of local residual stresses is the subject of an ongoing A.G.A. funded program at Battelle. Preliminary results indicate that moderate variation (up to 10 ksi) in surface residual stresses is possible from steel-to-steel or from specimen-to-specimen of a given steel, or even from the surface to a depth of 5 mils on a given specimen.[8]

In related research, it has been demonstrated that the introduction of surface residual compressive stresses by means of grit blasting or shot peening can be highly beneficial to the SCC resistance of a line pipe steel, see Figure 9. This approach to SCC mitigation is finding favor for new pipeline applications since the Almen strip intensity necessary to achieve measurable improvement in SCC resistance is readily obtained by means of the standard grit blasting procedures used prior to thin ... m epoxy coating application.

Role of the Near Surface Stress State

One curious aspect of SCC data obtained for smooth specimens in carbonate-bicarbonate is the dramatic decrease in cracking velocities (in the depth direction) observed with increasing test time, as shown in Figure 10. There is an equally dramatic increase in the number of cracks per specimen with increasing test time, as shown in Figure 11. This behavior seems to suggest that the conditions at the surface are conducive to the initiation of stress corrosion cracks but, as the crack penetrates into the specimen, the conditions in the bulk are much less conducive to crack propagation. These observations also are consistent with the results of metallographic examinations of secondary cracks from field failures. The length to depth aspect ratios for these larger cracks are considerably higher than one, as shown in Figure 12,[8] indicating much higher axial than radial cracking velocities.

One possible explanation for the behavior described above is related to the stress state within a test specimen or operating pipeline. Near the surface, plane stress conditions exist and plastic deformation occurs more readily than in the bulk where plane strain conditions constrain plastic flow. Thus, it appears that SCC in line pipe steels occurs more readily in the presence of plane stress conditions; an observation which is not particularly surprising considering the association of anodic SCC with crack tip creep, which is thought to be necessary to rupture the passive films present.

These observations have considerable implications for SCC testing since fracture mechanics type tests are commonly used and K is often considered to be an appropriate crack driving force parameter. However, K is a maximum at the root of a crack whereas the maximum crack velocities clearly occur near the free surface. Preliminary results of ongoing finite element analyses suggest that a parameter such as J may be more appropriate since it takes into account plastic deformation and more closely described the observed behavior.

CONCLUSION

Results of the studies described above have demonstrated that a number of surface properties affect the SCC susceptibility of line pipe steels. Moreover, these studies have shown that a knowledge of these effects can be used to develop procedures to mitigate SCC. These studies also point to the need for further research to develop better experimental techniques to enhance our understanding of specific phenomenon and develop more practical mitigation procedures.

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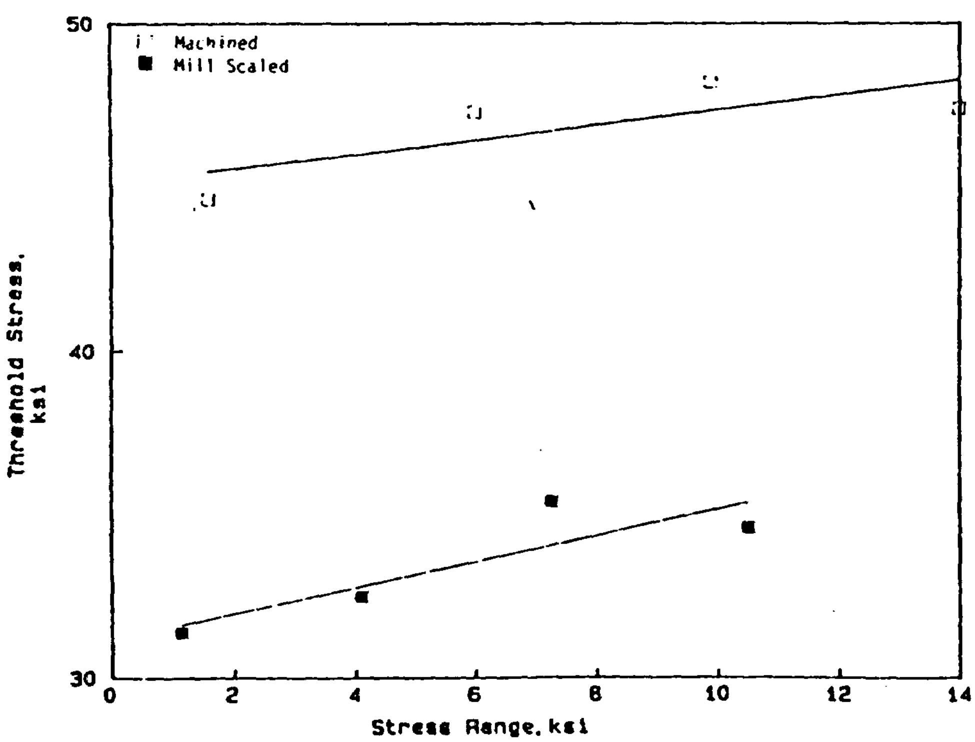

FIGURE 1.

EFFECT OF STRESS RANGE ON THE THRESHOLD STRESS FOR STRESS-CORROSION CRACKING OF MACHINED AND MILL SCALED SURFACES OF AN X-52 LINE PIPE STEEL (X-52T)

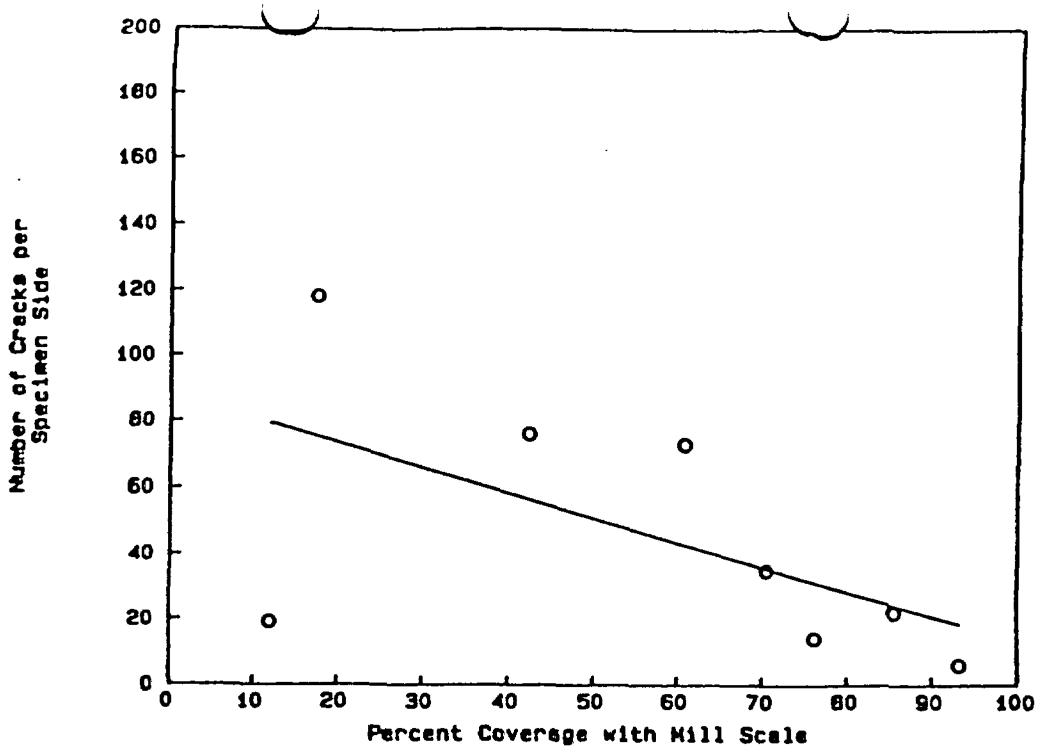

FIGURE 2. NUMBER OF CRACKS AS A FUNCTION OF MILL SCALE COVERAGE FOR AN X-60 STEEL (14)

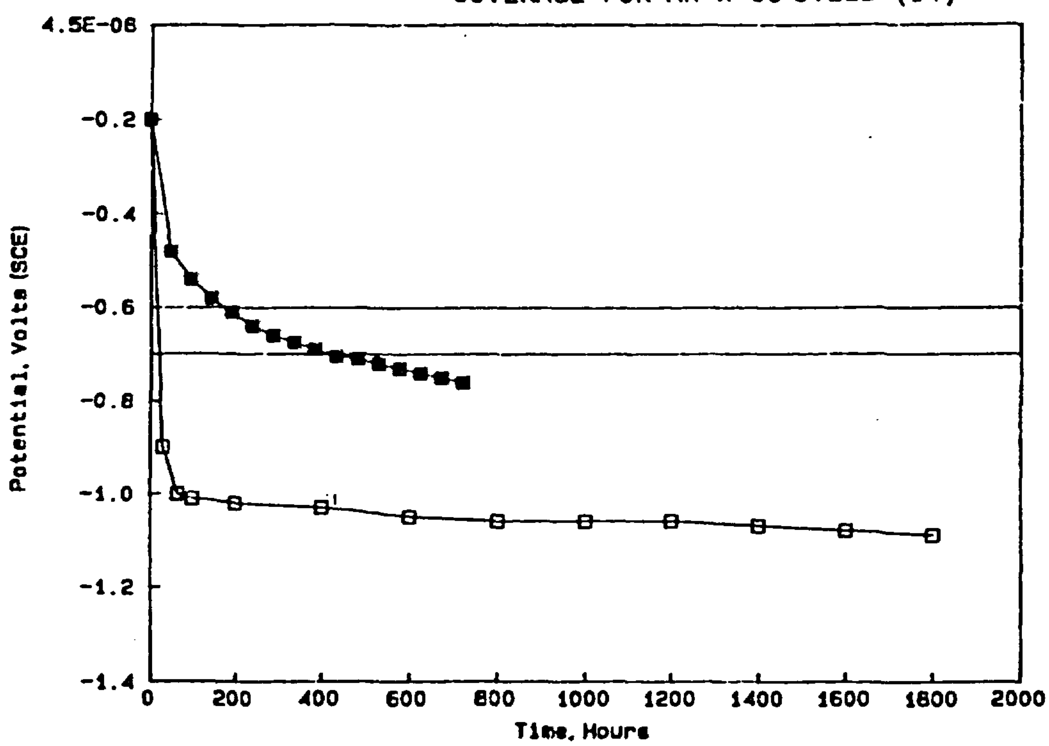

FIGURE 3. POTENTIAL AS A FUNCTION OF TIME FOR MILL SCALED AND BARE STEEL SURFACES EXPOSED IN 1N Na_2CO_3-1N $NaHCO_3$ AT A DISTANCE OF 20 cm FROM HOLIDAY IN 0.13 mm THICK ARTIFICIAL CREVICE: POTENTIAL AT HOLIDAY WAS MAINTAINED AT -850 mV (SCE)

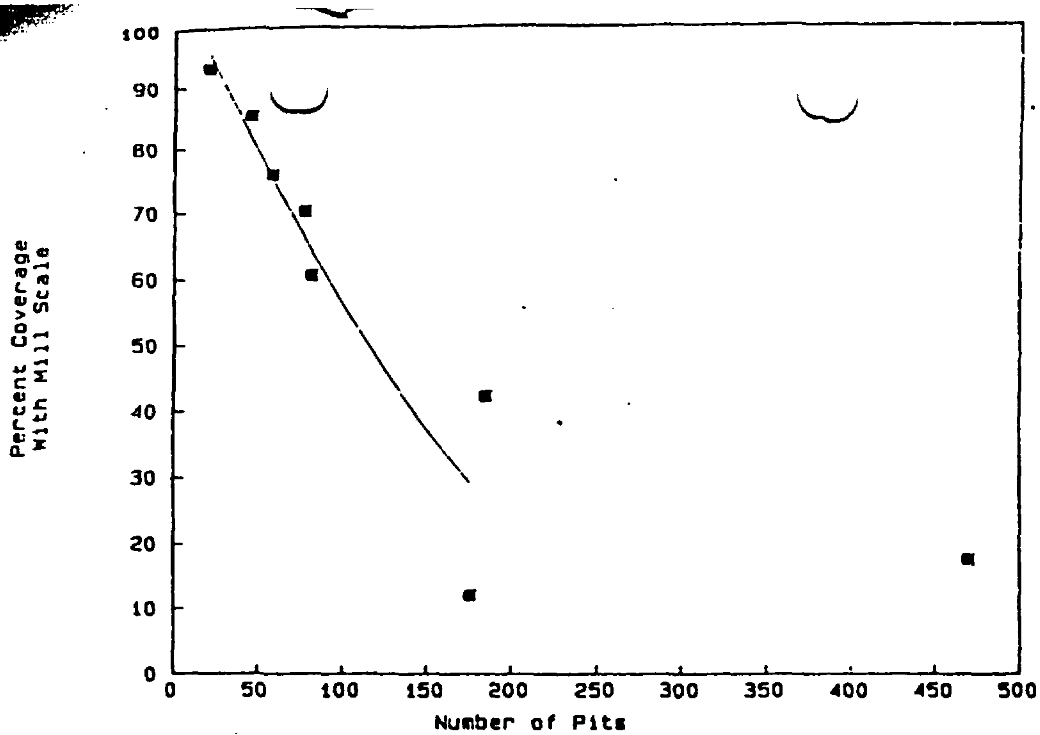

FIGURE 4. NUMBER OF PITS AS A FUNCTION OF MILL SCALE COVERAGE FOR AN X-60 STEEL (I4)[8]

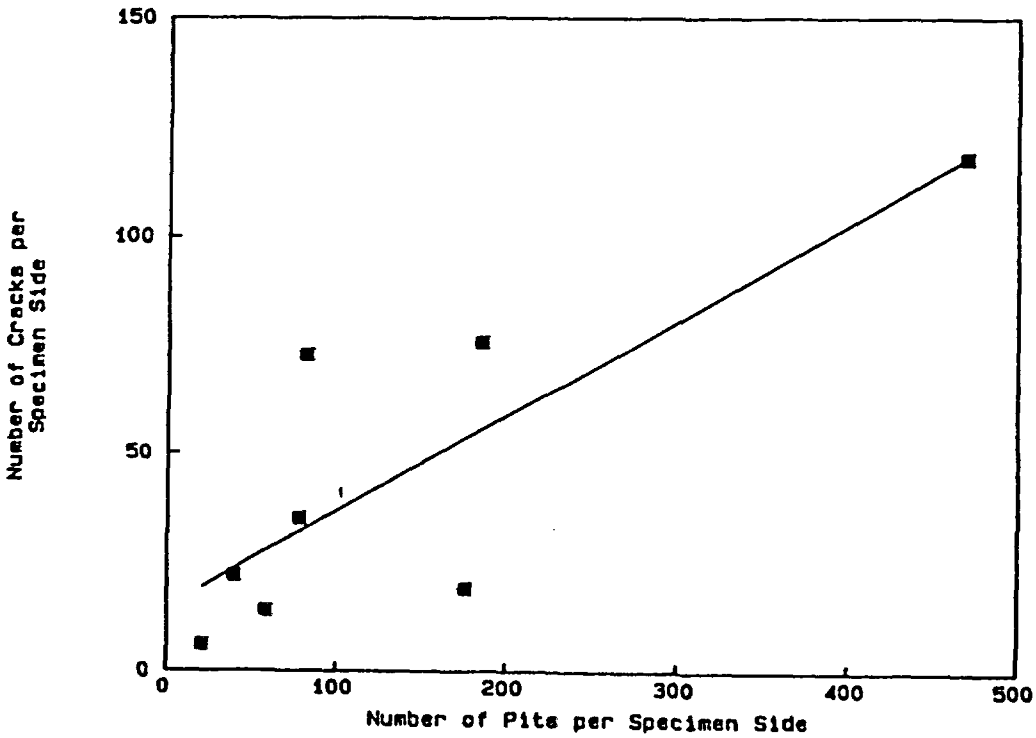

FIGURE 5. NUMBER OF CRACKS AS A FUNCTION OF NUMBER OF PITS FOR MILL SCALED SURFACES OF AN X-60 STEEL (I4)[8]

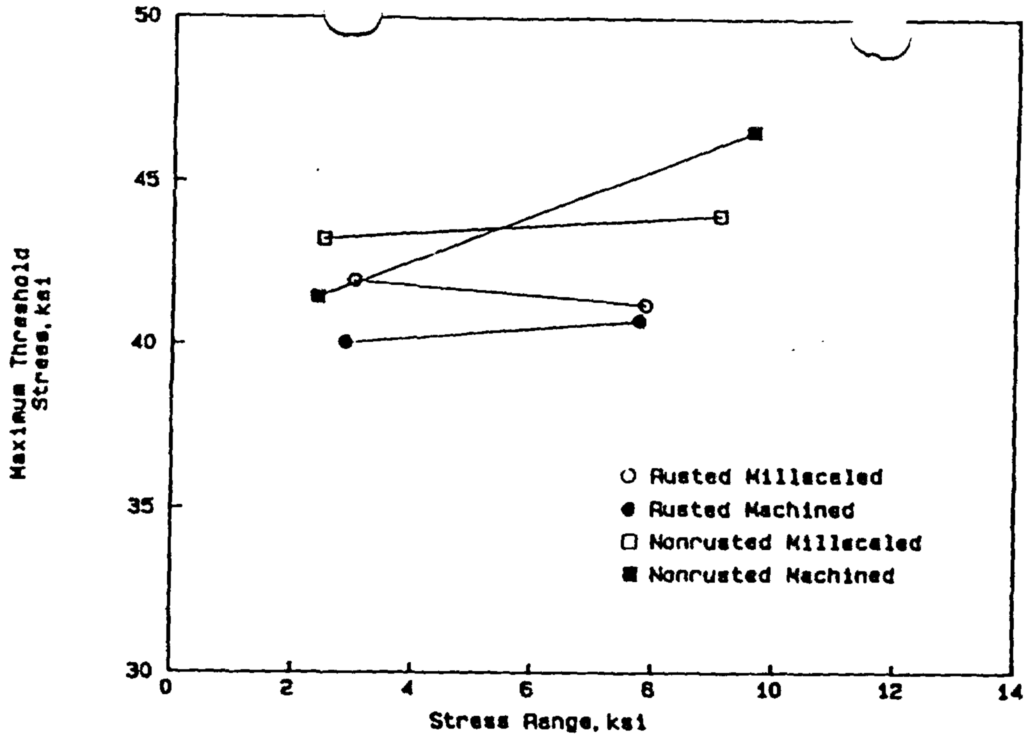

FIGURE 6. EFFECT OF STRESS RANGE AND SURFACE RUSTING ON THE THRESHOLD STRESS OF MACHINED AND MILL SCALED SURFACES OF AN X-52 LINE PIPE STEEL (X-52B)

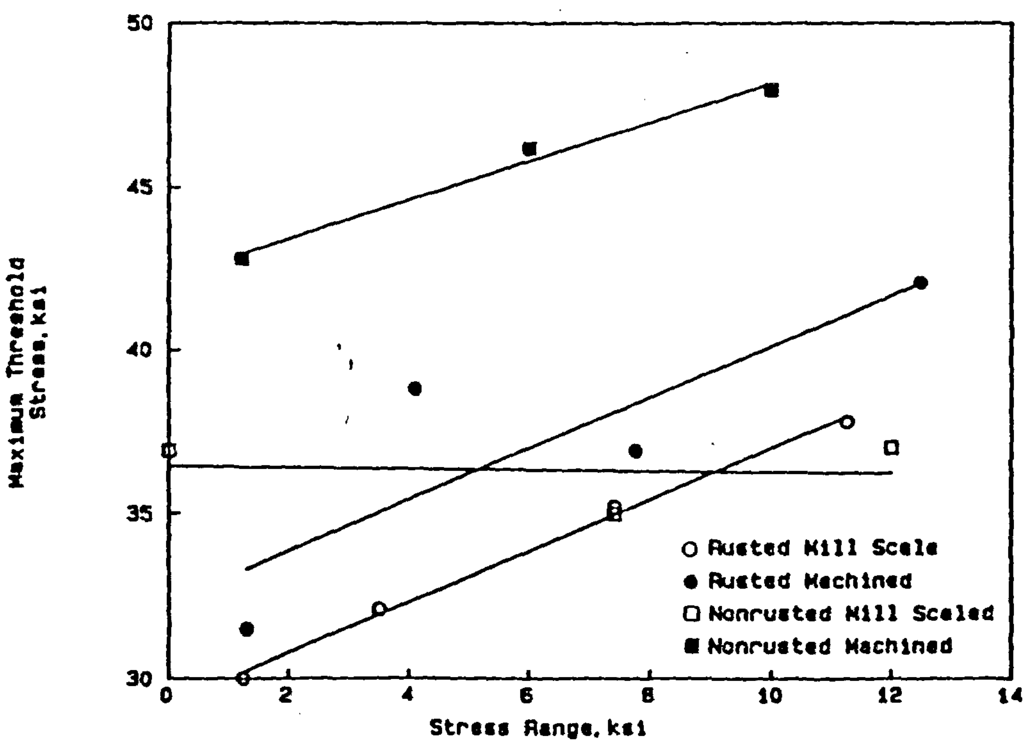

FIGURE 7. EFFECT OF STRESS RANGE AND SURFACE RUSTING ON THE THRESHOLD STRESS FOR SCC OF MACHINED AND MILL SCALED SURFACE OF AN X-52 LINE PIPE STEEL (X-52T)

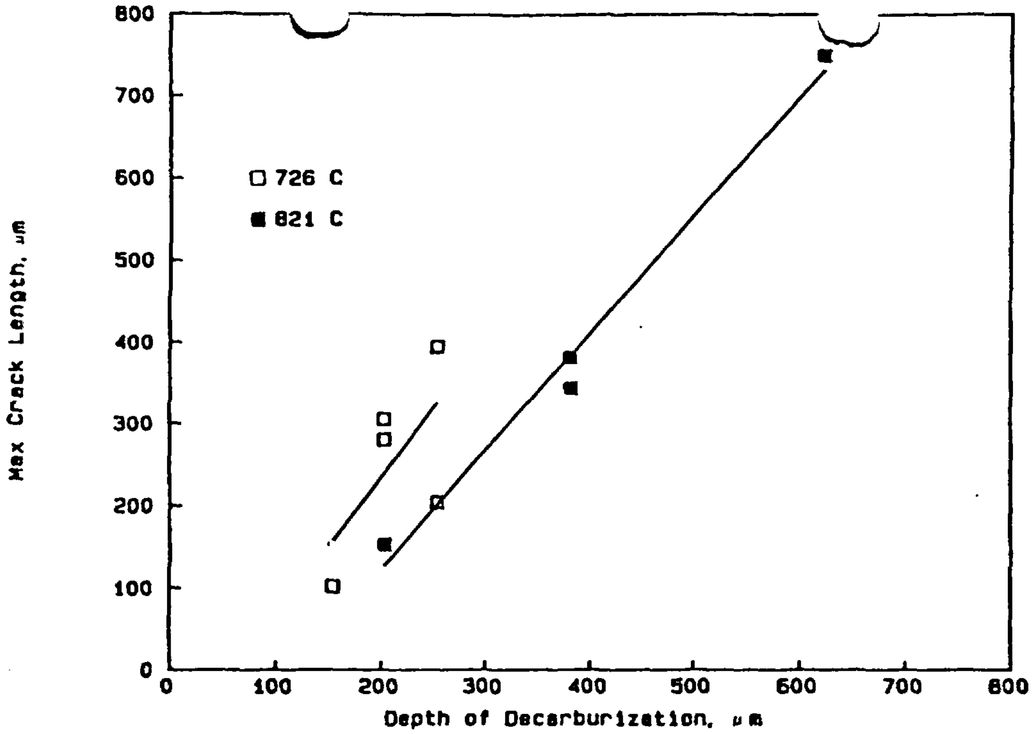

FIGURE 8. EFFECT OF SURFACE DECARBURIZATION ON STRESS CORROSION CRACK DEPTHS IN A LINE PIPE STEEL[11]

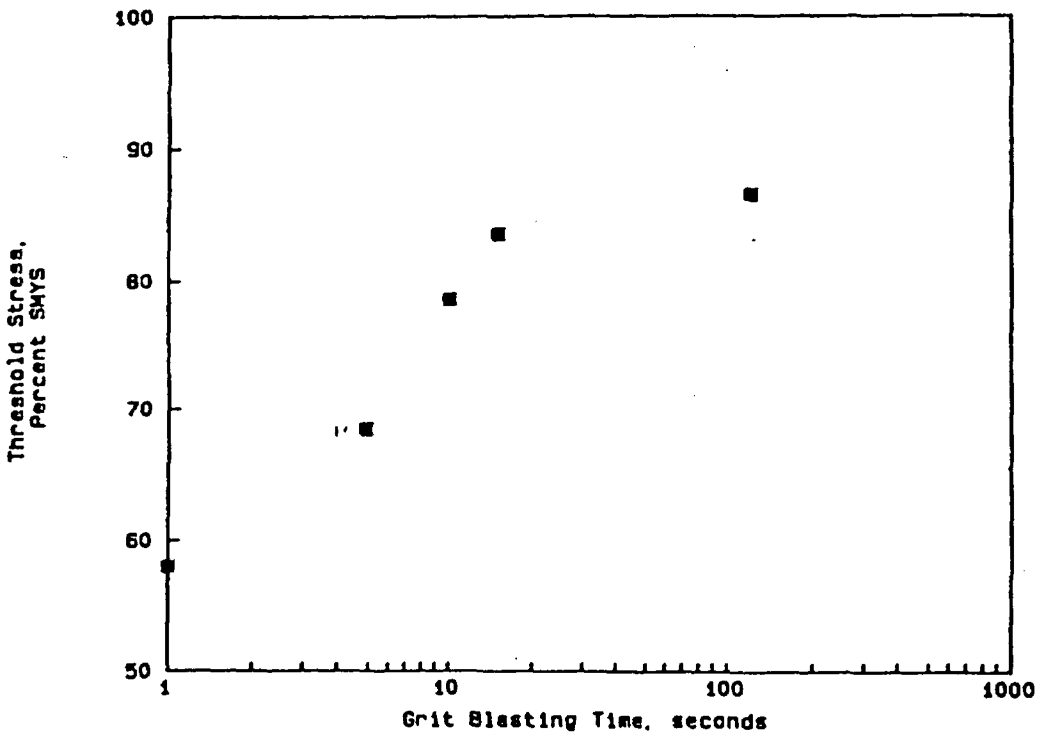

FIGURE 9. THE EFFECT OF GRIT BLAST TIME WITH G-25 GRIT SIZE ON THE THRESHOLD STRESS FOR SCC OF AN X-52 LINE PIPE STEEL[13]

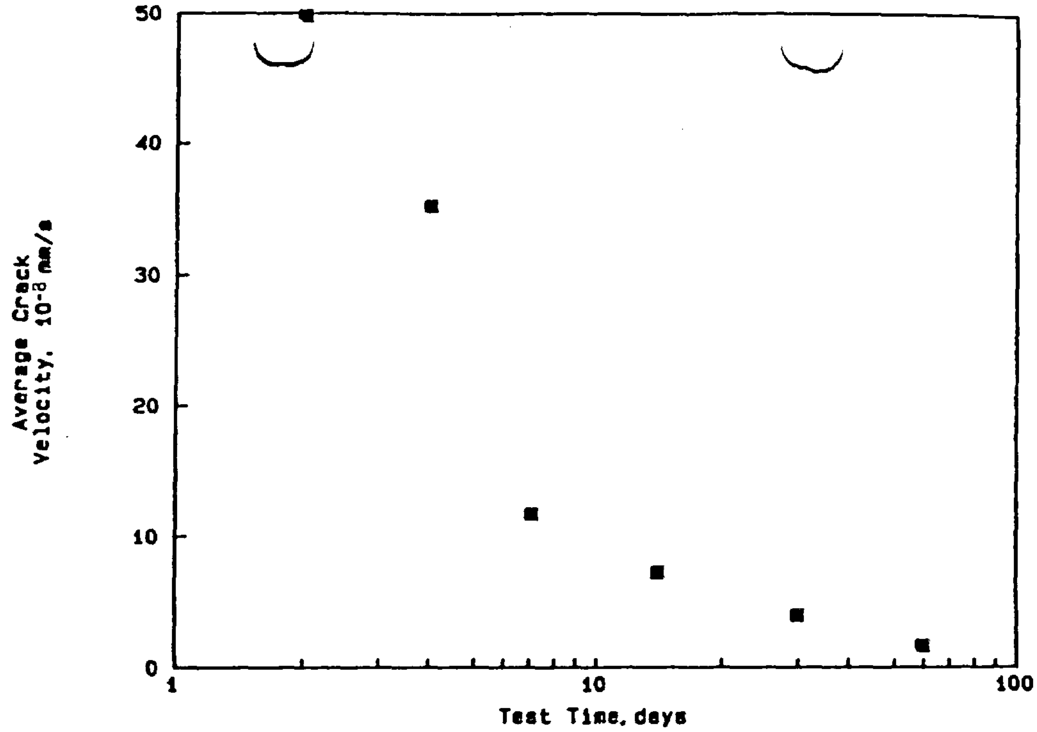

FIGURE 10. MAXIMUM CRACK VELOCITIES AS A FUNCTION OF TEST TIME FOR AN X-60 STEEL

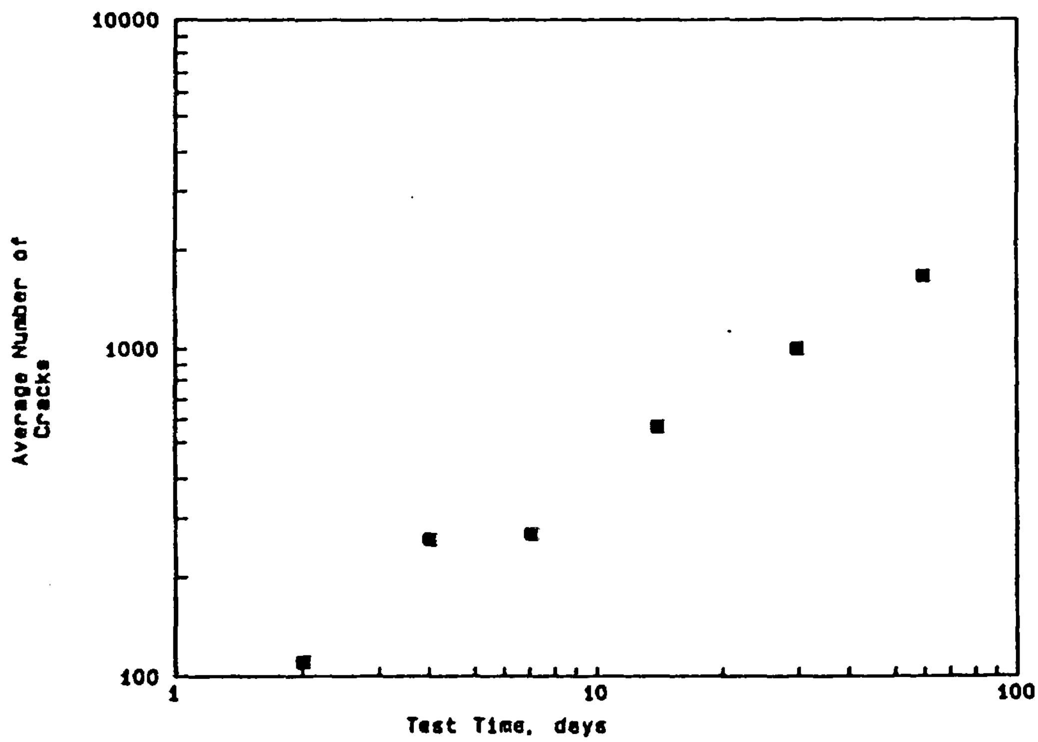

FIGURE 11. AVERAGE NUMBER OF CRACKS PER SPECIMEN AS A FUNCTION OF TEST TIME FOR AN X-60 STEEL (I4)

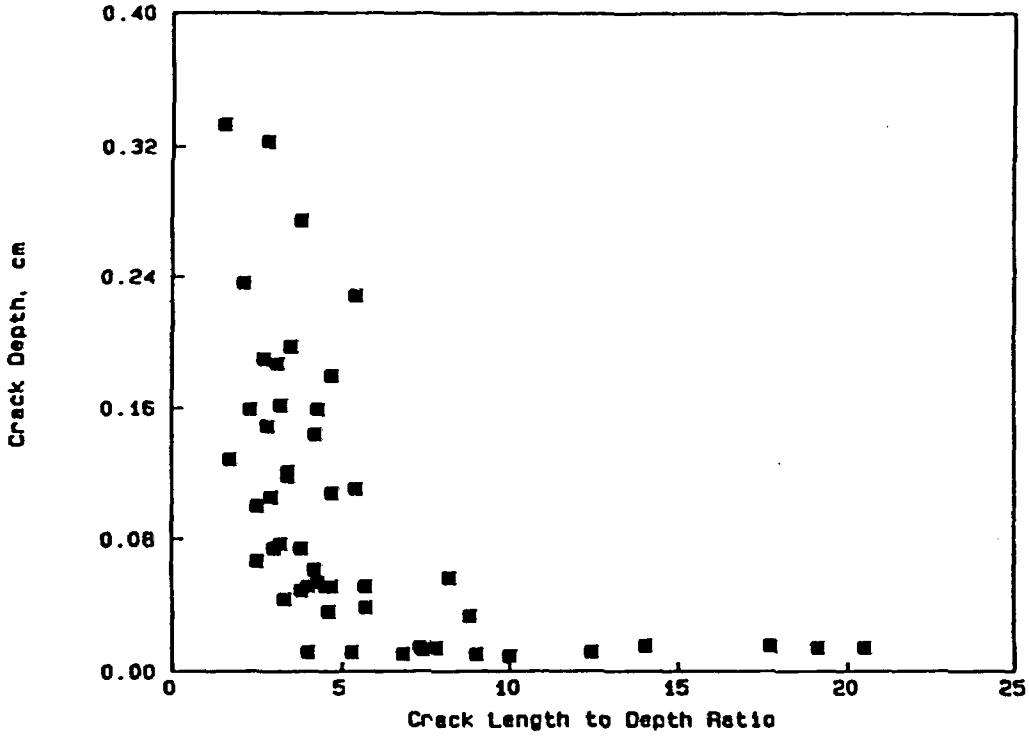

FIGURE 12. RELATIONSHIP BETWEEN CRACK DEPTH AND LENGTH TO DEPTH RATIO FOR SECONDARY CRACKS IN AN X-52 LINE PIPE STEEL THAT FAILED IN SERVICE[8]