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THE ROLE OF DISLOCATIONS IN TRANSGRANULAR STRESS CORROSION CRACKING OF AUSTENITIC STAINLESS STEELS

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THE ROLE OF DISLOCATIONS IN TRANSGRANULAR STRESS CORROSION CRACKING OF AUSTENITIC STAINLESS STEELS

by

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ABSTRACT

This report summarizes the Savannah River Laboratory studies that correlate dislocation substructure with transgranular stress corrosion cracking in austenitic stainless steel. Evidence is presented to show that the primary role of dislocations in the mechanism of cracking is to provide a continuous supply of localized anodic regions for selective electrochemical attack. The results show that cracking occurs preferentially on the $\{111\}$ family of planes and that dislocation movement, and therefore deformation, is required in the cracking process. Possible methods of reducing transgranular stress corrosion cracking include any process or alloy change that either inhibits dislocation movement, promotes cross slip, or reduces the tendency for corrosion.

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THE ROLE OF DISLOCATIONS IN TRANSGRANULAR STRESS CORROSION CRACKING OF AUSTENITIC STAINLESS STEELS

INTRODUCTION

Transgranular stress corrosion cracking has caused failures of several type 304 stainless steel components at the Savannah River Plant.(1) In an attempt to reduce these failures, the Savannah River Laboratory (SRL) is conducting a continuous investigation of this phenomenon.

Several SRL reports(2-6) relate specimen microstructure and dislocation substructure to stress corrosion susceptibility. Although the exact mechanism of cracking has not yet been established, the role of dislocation substructure in the cracking process is discussed extensively in the literature.(7-14) This report summarizes the studies at SRL that correlate dislocation substructure with stress corrosion susceptibility, discusses the role of dislocations in the cracking process, and suggests methods for minimizing the cracking.

SUMMARY

A variety of laboratory experiments and observations indicate that dislocation movements promote transgranular stress corrosion cracking by a mechanism of localized anodic dissolution along $\{111\}$ planes. It is proposed that the dislocation movements rupture the protective oxide film on the metal surface and produce anodic regions along the slip trace. These localized anodic regions then become the sites of preferential electrochemical attack.

Possible methods of reducing transgranular stress corrosion cracking include any process or alloy change that inhibits dislocation movement or promotes cross slip. For example, if coplanar dislocation movement occurs readily in a specific material, the movement of dislocations is progressive in a given slip plane and each successive dislocation further ruptures the protective film resulting in localized corrosion. In such a material, the susceptibility to transgranular stress corrosion would be high. However, if cross slip of dislocations can occur readily, coplanar motion is limited and the movement of dislocations in the material would rupture the protective film along numerous slip planes. This action would forestall the localization of corrosion along one particular slip trace and would therefore minimize transgranular stress corrosion cracking.

DISCUSSION

BACKGROUND

The importance of lattice defects in both chemical and physical processes is becoming increasingly apparent, and more studies of mechanisms include the influence of lattice imperfections. There is now little doubt that defects, particularly dislocations, are involved in the mechanism of transgranular stress corrosion cracking. In an early study, Forty(7) suggested that stress corrosion cracking of α-brass occurred because the chemical environment embrittled the metal locally to such an extent that dislocation pileups could produce stress concentrations sufficient to break down the local cohesion of the crystal structure.

Robertson and Tetelman(8) stated that "on a microscopic scale, the fracture process occurs on crystallographic planes, defined by the direction of the applied stress relative to the crystal orientation, and relative to the planes that operate to produce Cottrell-Lomer barriers." They suggested that these barriers act as sites for preferential chemical reactivity. Nielsen(9) showed that the initial stages of cracking occurred along the {111} <110> slip system which is in accord with corrosion down Cottrell-Lomer barriers. These reports suggested that samples having low stacking fault energies and the associated coplanar distributions of dislocations should be more susceptible to transgranular stress corrosion than samples having the tangled dislocation patterns associated with higher stacking fault energies.

Swann(10) provided direct experimental evidence of the relationship between dislocation substructure and susceptibility to transgranular stress corrosion. Using transmission electron microscopy techniques, he showed that "alloys with a cellular arrangement of dislocation tangles (high stacking fault energy) have superior resistance to transgranular failure, while alloys containing planar groups of dislocations (low stacking fault energy) are generally more susceptible."

Other investigators(11-13) have shown similar relationships between dislocation substructure and susceptibility to transgranular stress corrosion. Parkins'(14) excellent summary of stress corrosion cracking suggests that dislocations can influence cracking:

(1) by producing bursts of mechanical crack propagation; and/or

(2) by causing, directly or indirectly, intense localized electrochemical activity.

Despite a rather widespread acceptance of the importance of dislocation substructure in the transgranular stress corrosion mechanism, opinions vary about role of dislocations in the cracking process.

PROPOSED ROLE OF DISLOCATIONS

In an unstressed, polycrystalline, chemically homogeneous sample of austenitic stainless steel exposed to a solution known to cause transgranular stress corrosion cracking, the potentially most reactive sites will be grain boundaries, dislocations, and stacking faults, regions at a higher energy state than the matrix. However, since the entire surface of the specimen is protected by an oxide film, little corrosion will occur.

As stress is applied to the above sample, little corrosion occurs until the protective film is ruptured, exposing the underlying metal. Such rupture can occur if dislocations move to the metal surface and produce a slip trace, which is anodic to the matrix. Because this slip trace is a localized anode and represents a $\{111\}$ trace, the cracking process will begin by corrosion along that $\{111\}$ plane. If the stacking fault energy of the steel is low, cross slip does not occur readily; therefore, when one dislocation ruptures the protective film it is likely to be followed by another, then others, and corrosion proceeds down that particular slip plane. Such localized corrosion will produce a crack-like void in the metal, which causes a stress concentration in that region and enhances dislocation movement near the crack tip. At this time, the slip-corrosion process becomes cyclic, and transgranular stress corrosion cracking will occur. If the stacking fault energy is relatively high, however, cross slip will occur, and the protective film will be ruptured on numerous $\{111\}$ traces so that localization of corrosion along one particular $\{111\}$ plane is unlikely, and little or no stress corrosion cracking will result.

In addition to the influence of dislocation movement, the dislocations and stacking faults themselves will be regions of anodic activity because of the strain energy associated with them. This resultant higher chemical activity should cause localized corrosion along defects, even when movement of the defects does not occur. This chemical attack is affected by segregation of solute atoms at the defects(15,16) which may either increase or decrease the chemical activity, depending on the nature of the segregating atoms. In cases of increased chemical activity, localization of corrosion along the defect should be expected, which would in turn increase the susceptibility to stress corrosion cracking.

Therefore, the role of dislocations in transgranular stress corrosion cracking is to provide a continuous supply of localized anodic sites which allow crack initiation and propagation to occur by electrochemical dissolution.

EXPERIMENTAL PROCEDURES

The materials used in this study were AISI types 304, 304L, 316, and 316L stainless steels, "Tenelon"*, and a 16Cr-20Ni steel. All samples were water quenched from 1010°C, except when other heat treatments or deformation conditions are noted.

Three specimen designs were used for most of the studies:

- Square sheet samples approximately 1/2 x 1/2 x 0.06 inch with dry-ground surfaces.
- U-bend samples having the design shown in Figure 1.
- Thin foils prepared by wet grinding, mechanical polishing, and electrochemical thinning.

Specimens were exposed to solutions of various salts in deionized water. Time and stress conditions were varied. Exposure effects were determined by optical and electron microscopy techniques. Further details are given below.

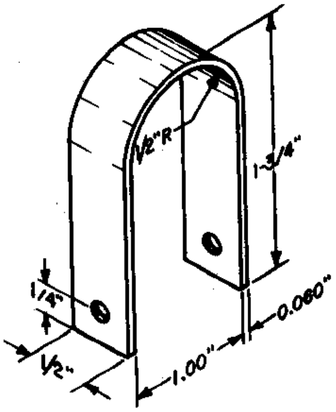

FIG. 1 DIMENSIONS OF U-BEND SPECIMEN

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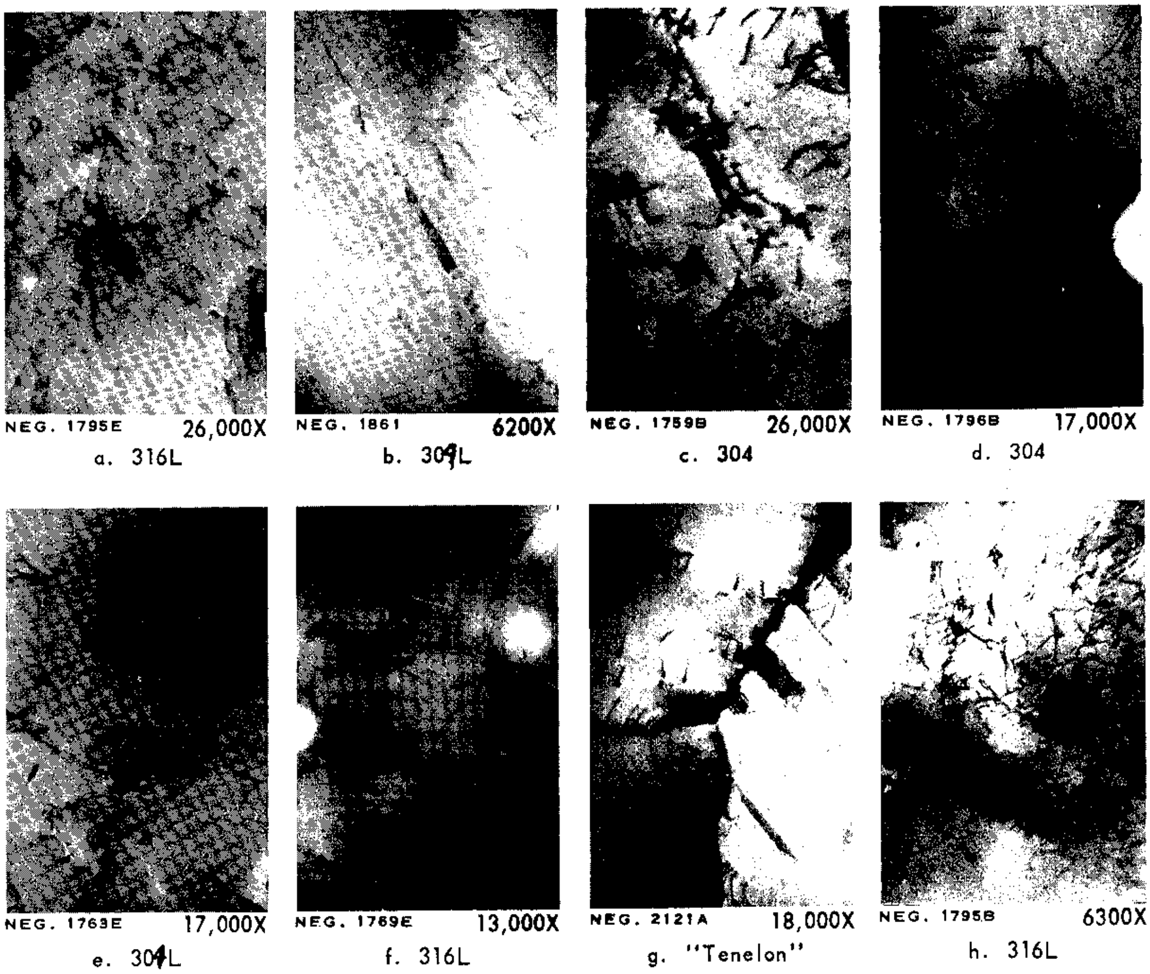
*"Tenelon" is a patented, nickel-free austenitic stainless steel having the nominal alloy composition of: C=0.08-0.12, Mn=14.50-16.00, P=0.045 max. S=0.03, N=0.75 max., Si=0.30-1.00, N=0.35 min, Cr=17.00-19.00, Fe=balance.

EVIDENCE SUPPORTING PROPOSED ROLE

Thin Foil Studies

Thin foils of annealed-and-quenched or cold-rolled austenitic stainless steels were prepared by electropolishing mechanically thinned foils (~1-2 mils thick) in a H_2SO_4-H_3PO_4-H_2O solution until the foils were thin enough for electron transmission (~1000 Å). Typical as-thinned structures are shown in Figure 2. Coplanar dislocation arrays were observed in all foils, and stacking faults and extended dislocation nodes were apparent in all but the type 316 and the 16Cr-20Ni steels. These dislocation arrangements are indicative of low stacking fault energies(17) and suggest that the alloys should be susceptible to transgranular stress corrosion cracking in chloride solutions.(8,10-14)

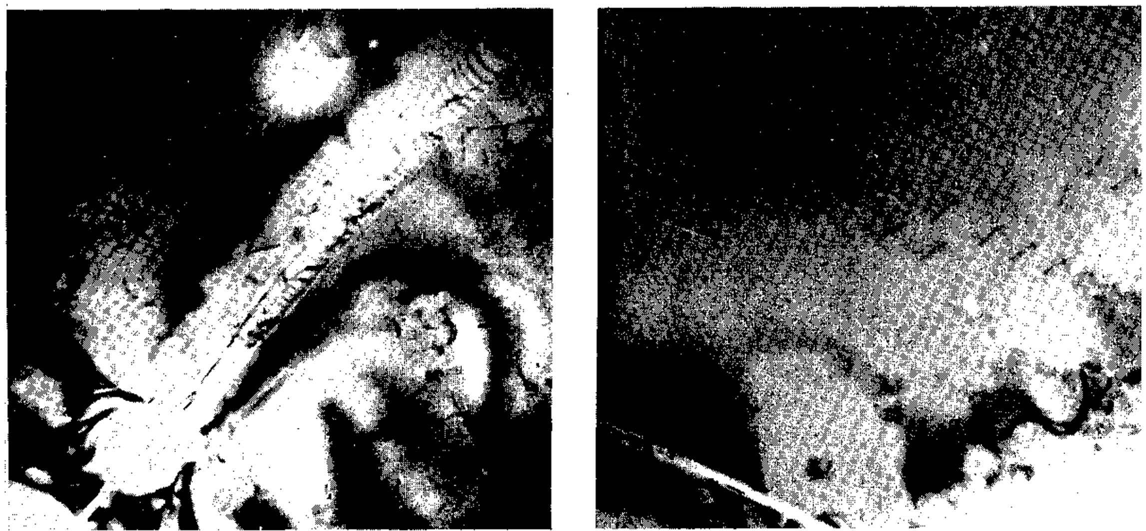


a. 316L b. 304L c. 304 d. 304

e. 304L f. 316L g. "Tenelon" h. 316L

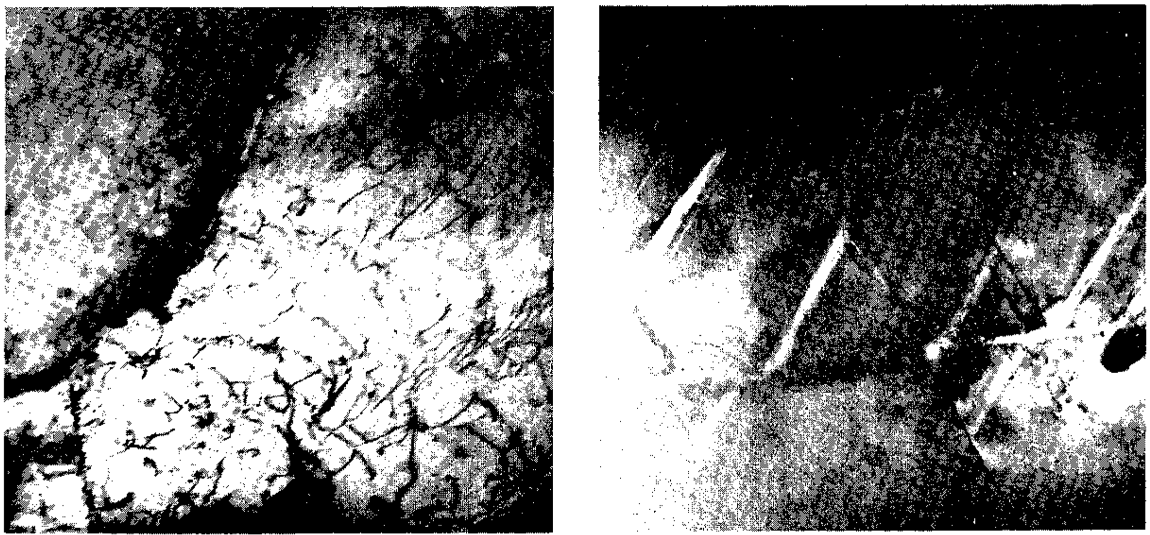
FIG. 2 TYPICAL DISLOCATION SUBSTRUCTURE IN AUSTENITIC STAINLESS STEELS

Regions of preferential attack by the electropolishing solution were observed (Figure 3) primarily along $\{111\}$ traces and were generally associated with dislocation pileups, stacking faults, and/or slip traces.



a. Preferential attack along dislocation pileup.

b. Preferential attack along stacking fault.



c. Preferential attack along grain boundary in sensitized steel.

d. Preferential attack along several $\{111\}$ traces.

FIG. 3 PREFERENTIAL ATTACK AT VARIOUS STRUCTURAL FEATURES IN AUSTENITIC STAINLESS STEELS. This attack occurred during electrochemical thinning of the foils.

Exposure of the thinned foils to dilute chloride solutions caused further preferential attack to occur along $\{111\}$ traces by pitting and the formation of crack-like voids.

The 0.06- to 0.07-micron pits that were produced (Figure 4) were approximately the same as the 0.05-micron pits reported by Nielsen(18) for corrosion tunnels along the $\{111\}$ $\langle 110 \rangle$ slip system. Nielsen's work has been interpreted as evidence for corrosion along Cottrell-Lomer barriers,(14) thus giving some support to the Robertson-Tetelman(8) mechanism of cracking. However, no Cottrell-Lomer barriers were observed in the pitted foils; in fact, foil-tilting experiments showed that pitting was more directly related to dislocation traces than to the dislocations themselves.

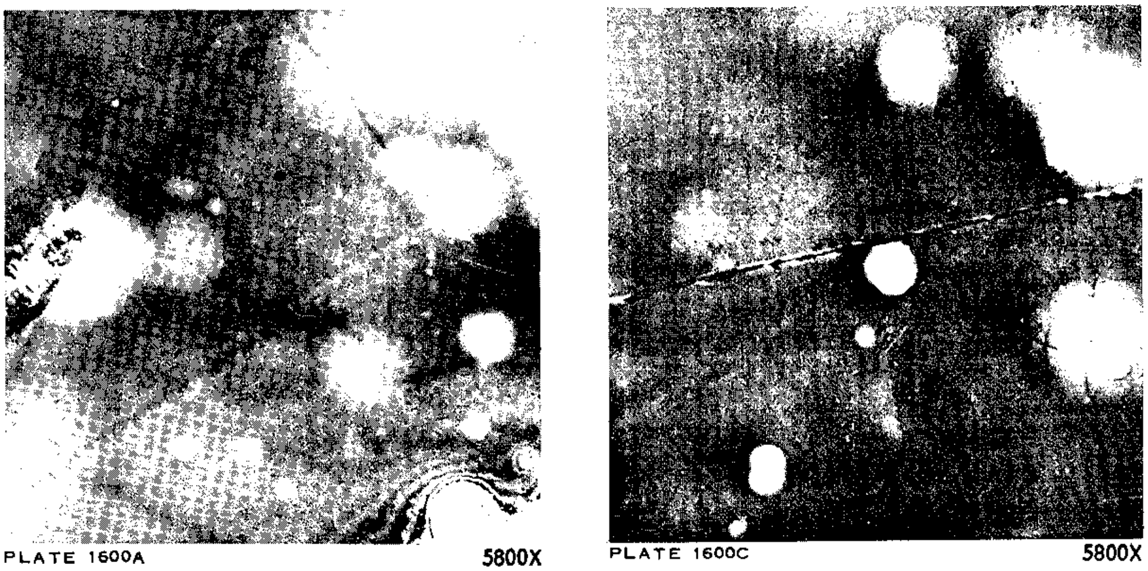


PLATE 1600A 5800X

PLATE 1600C 5800X

FIG. 4 PREFERENTIAL PITTING ALONG $\{111\}$ TRACES IN TYPE 304 STAINLESS STEEL FOIL EXPOSED TO DILUTE CHLORIDE SOLUTION AT 100°C

The bending of foils in the boiling chloride solutions probably caused dislocation movement to occur. Such dislocation movement could rupture the protective film on the foil surface, producing $\{111\}$ traces anodic to the matrix. We interpret the pitting that occurred along such traces as the initial stage of the formation of crack-like voids observed in other foils exposed to chloride solutions.

Further experimental evidence supporting the proposed mechanism (that dislocations provide local anodic sites at which cracks initiate by electrochemical dissolution) was obtained with foils exposed to boiling solutions of 100 ppm NaCl and $\sim$40 ppm platinic acid in deionized water. Platinum was preferentially precipitated adjacent to slip traces (Figure 5) showing that such traces were anodic to the matrix (Nielsen(18) had demonstrated that platinum precipitated near anodic regions). The platinum precipitated nonuniformly along the slip trace; the spacing was similar to that of corrosion pits caused by platinic-acid-free chloride solutions.

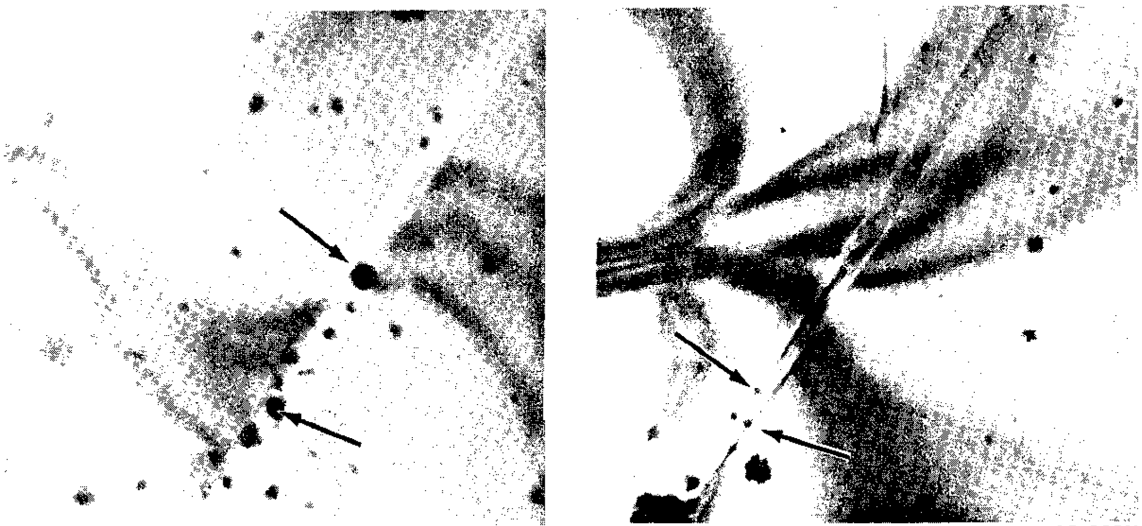


PLATE 2002B 37,000X PLATE 2002D 37,000X

FIG. 5 PHOTOMICROGRAPHS ILLUSTRATING PLATINUM DECORATION OF ANODIC SITES. The black dots (see arrows) on the sample are regions where platinum has deposited during exposure and the light lines along the photographs are slip traces.

These results and similar observations by other investigators(19,20) support the proposed role of dislocations by showing that reactive sites can be created by dislocation movement.

Although pitting was observed in several foils during chloride exposure, formation of crack-like voids along $\{111\}$ traces (Figure 6) was more common. These voids were interpreted as stress corrosion cracks because chloride was an essential ingredient; similar chloride-free solutions did not cause such cracks. The cracks were quite similar to those formed during electropolishing, and the results of the exposures show that localized corrosion plays a dominant role in the cracking process.

The following observations were made:

1. The severity of cracking increased with increasing exposure time, and existing cracks propagated during subsequent exposures (Figure 7).

PLATE 1862 7800X

a. Sample exposed 30 minutes in 100 ppm NaCl solution at 100°C.

PLATE 1799D 33,000X

b. Sample exposed 5 minutes in 100 ppm NaCl solution at 100°C.

FIG. 6 EXAMPLES OF CRACKING CAUSED BY EXPOSURE TO NaCl SOLUTIONS. Arrows point to cracked regions (additional examples to be given in figures to follow).

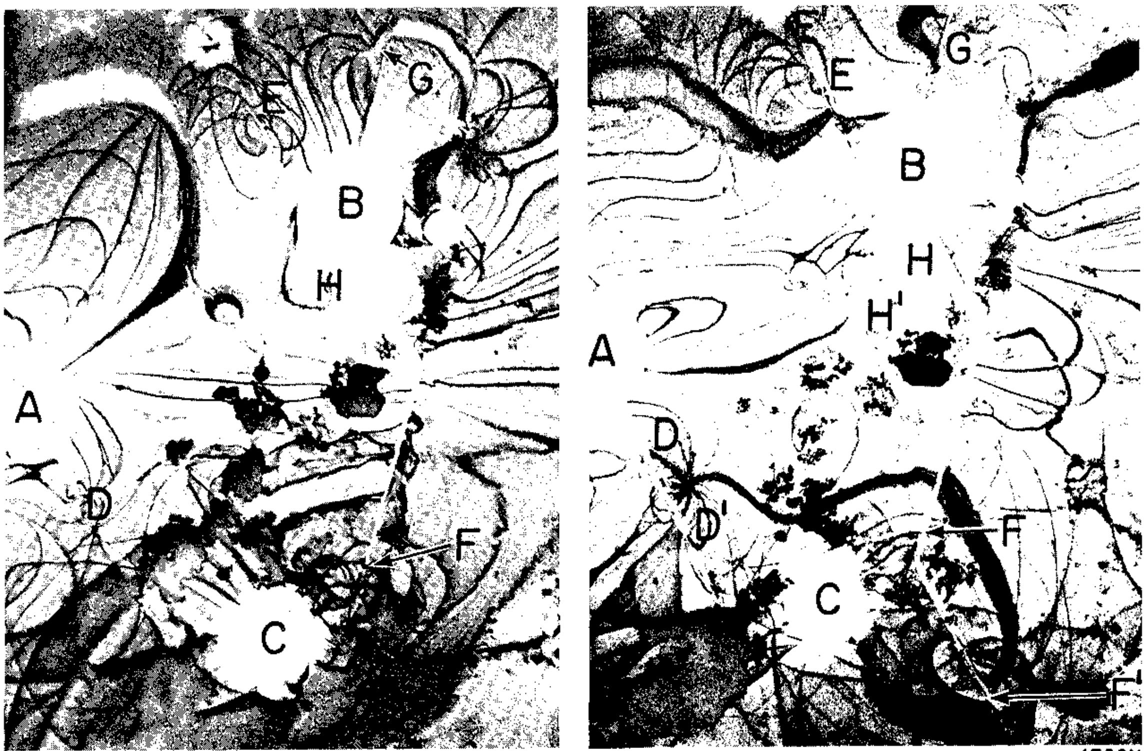


PLATE 1714C 6700X

PLATE 1715B 6700X

FIG. 7 PROPAGATION OF EXISTING CRACKS IN TYPE 304 STAINLESS STEEL FOIL DURING EXPOSURE TO A SOLUTION OF DEIONIZED WATER AND 100 ppm CHLORIDE (as NaCl) AT 100°C. Note that after 15-minute exposure crack propagated from holes A, B, and C, and ended at D, E, F, G, and H, and after 25-minute exposure the cracks had propagated to D', E', F', and H'.

2. The extent of cracking decreased when the temperature decreased (Figure 8).

3. Cracks preferentially propagated along regions containing defects and were most often associated with mobile dislocations (Figure 6).

4. Corrosion product was often seen within the cracks (Figure 9).

These observations, together with those of other investigators(12,19,21) are consistent with the proposed dislocation movement-film rupture-corrosion sequence of cracking, i.e.:

a) mobile defects and {111} cracking show the role of dislocation movement

b) the observation of corrosion product shows that corrosion had occurred, and

c) the temperature effect shows that the corrosion and/or dislocation mobility increases with increasing temperature.

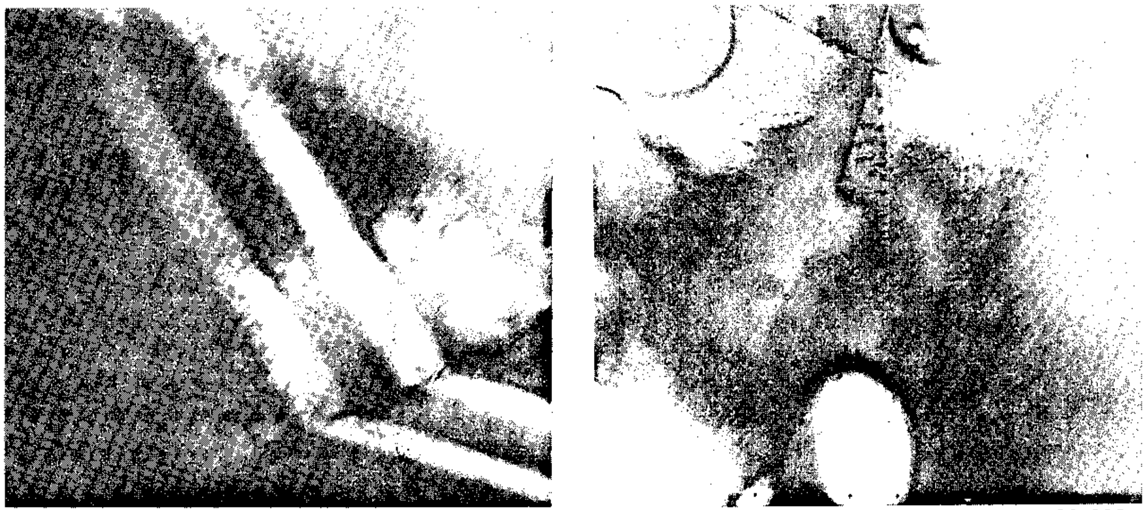


PLATE 1799F **21,000X**

a. Preferential attack in foil exposed for 5 minutes at 100°C. Attack of this type was apparent throughout the foil.

PLATE 1798B **11,000X**

b. Preferential attack in foil exposed for 20 minutes at 20°C. This region was the most aggressively attacked region in the foil.

FIG. 8 EFFECT OF TEMPERATURE ON THE PREFERENTIAL ATTACK ALONG {111} PLANES IN TYPE 304 STAINLESS STEEL FOILS EXPOSED TO A SOLUTION OF DEIONIZED WATER AND CHLORIDE ION. (These micrographs are from the same foil which was thinned, then sectioned. Half the foil was exposed at 20°C and half at 100°C).

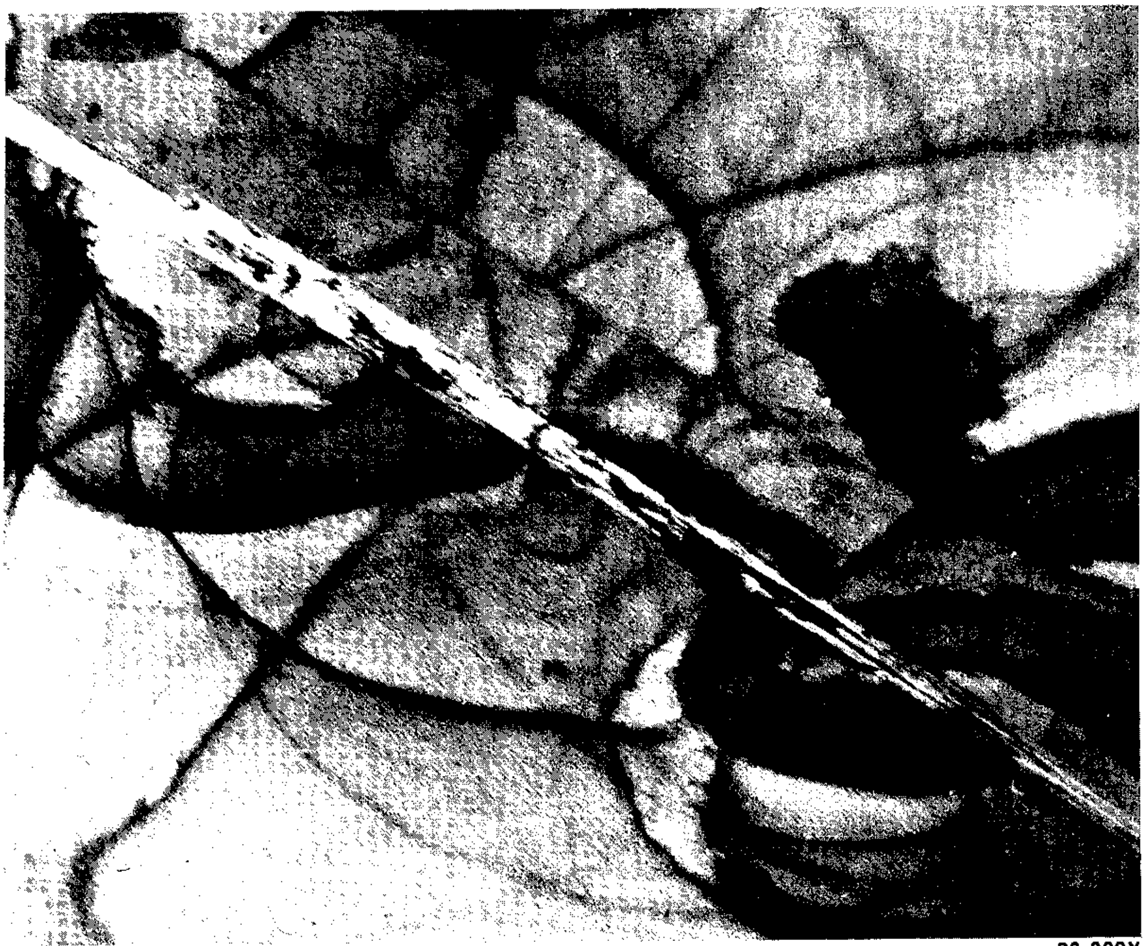


FIG. 9 ASSOCIATION OF CORROSION PRODUCT WITH CRACKING

Previous tests(5) showed that the same qualitative differences in the relative susceptibility to cracking were found in thin foils and in bulk samples prepared from various heats of steel. Because the mechanical aspects of fracture in thin foils and bulk samples are quite different, this result provides further evidence that the primary role of dislocations is to provide active corrosion sites rather than to produce mechanical rupture.

Studies with Massive Specimens

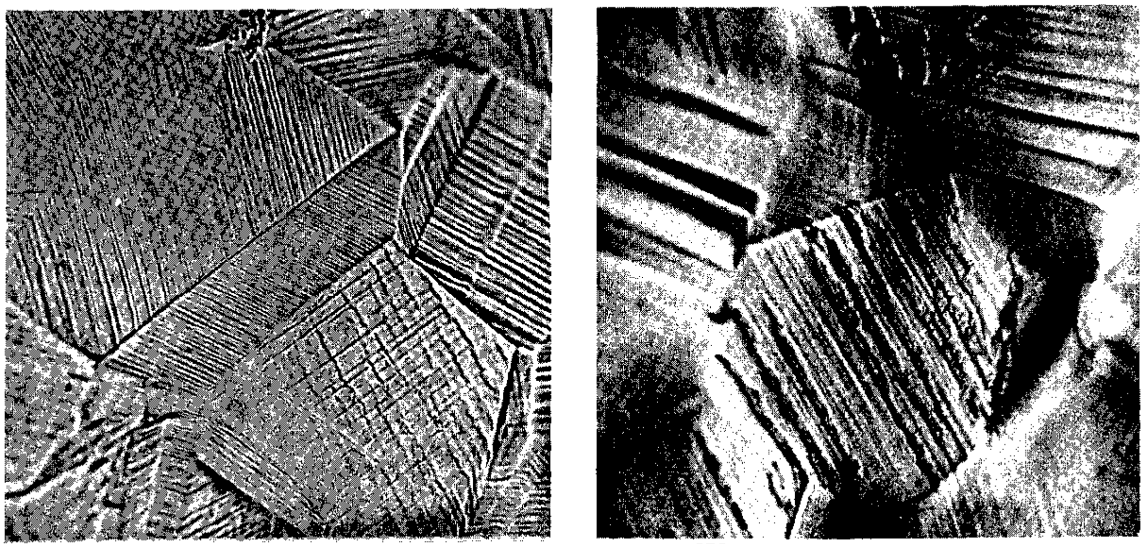
U-bend samples of type 304L stainless steel were exposed for 5, 15, and 30 minutes to 42% solutions of $MgCl_2$ at 154°C. The surfaces of the samples were polished for metallographic observation prior to being formed into the U-shape. The samples contained incipient stress corrosion cracks after the 5-minute exposure, and well-developed branched transgranular cracks after 30 minutes. Metallographic examination of the exposed surfaces revealed that cracking occurred in the following manner:

1. Corrosion pitting occurred initially in localized areas (Figure 10a).
2. Pitting was followed by extension of the corrosion to form linear traces of corrosion product on the sample surfaces; the traces were often parallel to observable slip traces (Figure 10b).
3. Additional exposure caused cracking to occur in the corroded regions (Figure 10c).
4. At still longer exposures, the small cracks within each grain connected to form branching, transgranular cracks (Figure 10d). Although the crystallographic nature of the cracks was no longer readily apparent at this stage, the branches often changed directions at grain boundaries, and many were parallel to slip traces.

The traces of the incipient cracks were indexed, and in all cases were aligned within ±2° of $\{111\}$ traces. This observation, coupled with the observation that the formation of corrosion products accompanies crack growth, provides additional evidence that the $\{111\}$ plane is made anodic by dislocation movement and that subsequent corrosion occurs in that region.

Another supporting observation is that often one grain would contain five or six incipient cracks, while adjacent grains showed none. This could result from differences in the resolved shear stress on the $\{111\}$ planes in different grains. Cracking would occur only in the grain(s) where the resolved shear stress on the $\{111\}$ plane was high enough to produce slip (dislocation movement) during exposure. If this were the case, one would expect to find regions where cracking occurred only in grains with certain orientations; such regions were found throughout the samples as shown in Figure 11.

Additional evidence for $\{111\}$ fracture was found by trace analysis of sectioned U-bend samples (Figure 12). The crystallographic nature of the cracking was much more apparent in samples that cracked slowly(27) than in samples that cracked rapidly; however, $\{111\}$ fracture was observed in 50-mil-thick U-bend samples that had fractured after exposures varying from 2 hours to several weeks.

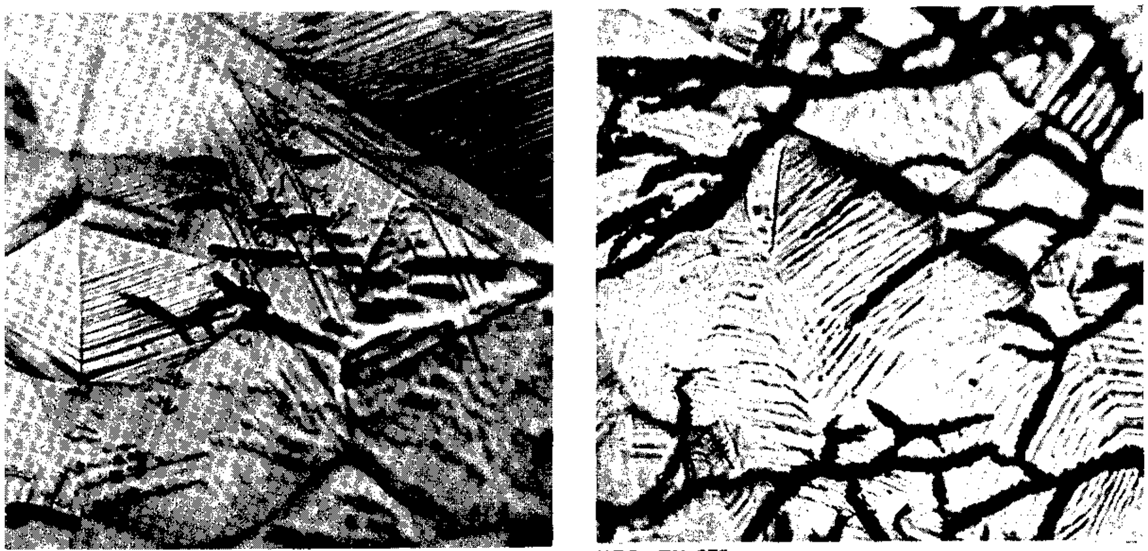


NEG. EM-268

a. The initial stage - pitting in very localized regions. Exposure 5 minutes.

NEG. EM-270

b. Extension of pits to form lines of corrosion. Exposure 15 minutes.



NEG. EM-271

c. Initiation of cracks within corroded areas. Exposure 15 minutes.

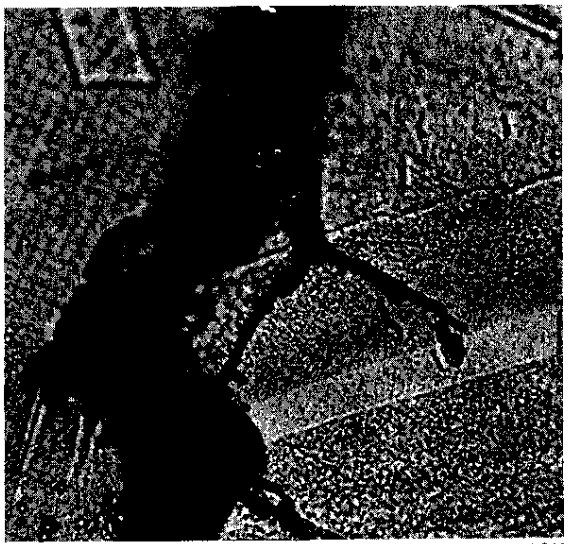
NEG. EM-275

d. Pattern of well - developed cracks. Exposure 30 minutes.

FIG. 10 SEQUENCE OF CRACK INITIATION IN TYPE 304 STAINLESS STEEL U-BEND SPECIMENS EXPOSED TO 42% $MgCl_2$ SOLUTIONS AT 154°C (500X)

NEG. EM-273 250X

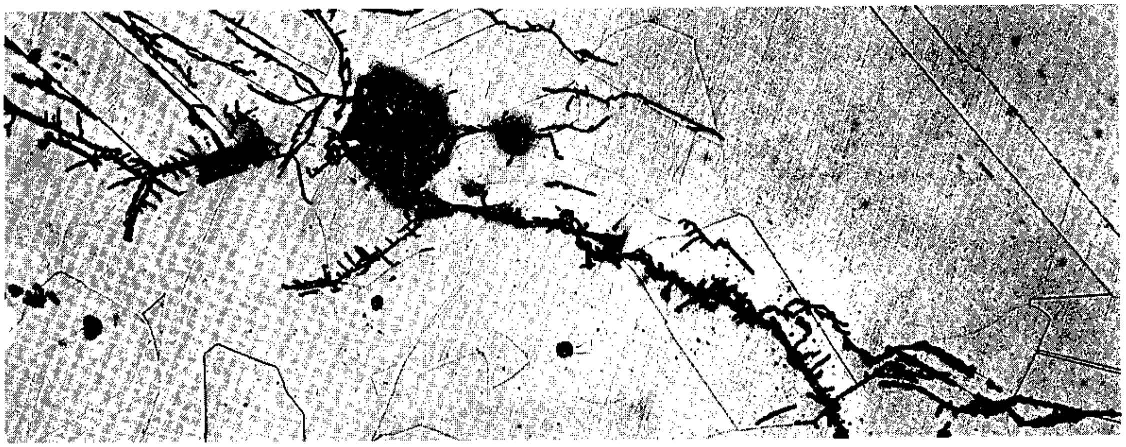
FIG. 11 RELATIONSHIP BETWEEN GRAIN ORIENTATION AND SUSCEPTIBILITY TO STRESS CORROSION IN BOILING 42% $MgCl_2$ SOLUTIONS. Note that many of the cracks are nearly parallel to each other and are in groups A, B, C, and D which have similar orientations with respect to the specimen surfaces.



NEG. EM-255 500X

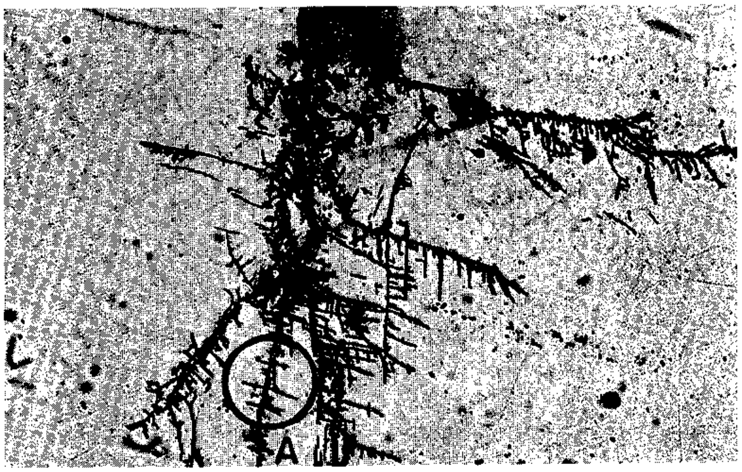
FIG. 12 EXAMPLE OF CRACKING ALONG THE FOUR {111} TRACES IN A GIVEN GRAIN

The crack morphology was studied in samples where the cracks propagated more slowly. The samples were mechanically polished and electrolytically etched in 10% oxalic acid for observation. Cracks changed directions at grain and twin boundaries and many cracks were parallel to twin traces (Figure 13a). The traces of several of the cracks formed pronounced Widmanstätten patterns (Figure 13b), and as many as four crack directions were visible within a given grain. The maximum number of trace directions in a Widmanstätten pattern is a function of the crystallographic habit plane of the pattern; the observation of four traces indicated that cracking occurred on the $\{111\}$ plane.(29)



NEG. EM-2

a. Transgranular stress corrosion cracks in specimen exposed 16 hours to 100-ppm chloride solution (10% oxalic acid etch).



NEG. EM-20

b. Widmanstätten pattern of cracking in specimen exposed 168 hours to 100-ppm chloride solution (10% oxalic acid etch). Note the four crack directions in Region A.

FIG. 13 STRESS CORROSION CRACKS IN ROUGH DRY GROUND SAMPLES EXPOSED TO CHLORIDE SOLUTIONS (250X)

The repeated observation of {111} fracture was somewhat surprising because several investigators(22-26) had studied the crystallography of stress corrosion cracking and had observed fracture on {111} planes,(25) on {100} planes,(23) and on no particular crystallographic plane.(22,24,26) The metallographic examinations in these studies were made at relatively low magnifications and on well-developed cracks. Such observations do not refute the proposed role of dislocations because microscopic fracture on two or more different {111} planes could cause the fracture to appear to lie on another crystallographic plane or on no particular plane; this behavior is clearly illustrated in Figure 14.

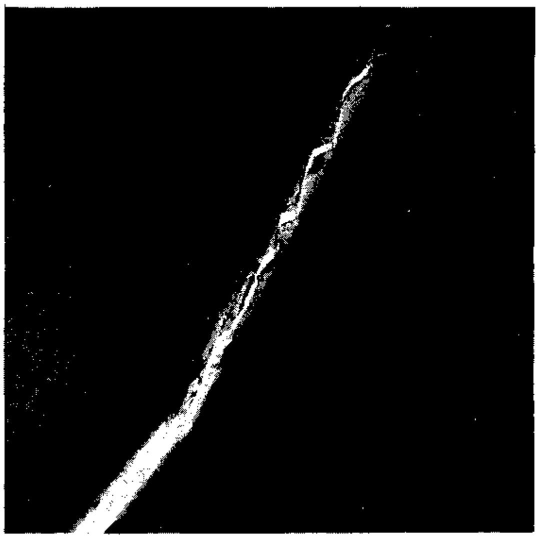


FIG. 14 ALTERNATE FRACTURE ALONG TWO {111} PLANES (A & B) PRODUCING CRACK WHICH APPARENTLY LIES ON ANOTHER PLANE (C).

SHORTCOMINGS OF PROPOSED ROLE

The results of the SRL studies and many other investigations(7-14,18-20,28) have shown that lattice defects play an important role in stress corrosion processes; however, results reported in DP-957(5) and by other investigators(19,30) have shown that different heats of steel with the same nominal alloy compositions(5,30) and with similar stacking fault energies(5,19) have different susceptibilities to transgranular stress corrosion cracking. Thus, some variable(s), in addition to dislocation substructure, must influence the susceptibility to transgranular stress corrosion cracking, and the proposed role of dislocations is therefore not a complete explanation of the mechanism of transgranular cracking. The influence of variables such as impurity content, second-phase distributions, alloy segregation, and solution chemistry must be understood before a complete mechanism can be derived.

POSSIBLE METHODS FOR MINIMIZING STRESS CORROSION

Nickel Content

It has been shown that an increase in nickel content increases both the resistance to stress corrosion and the stacking fault energy of austenitic stainless steel. These observations led to the conclusion that the beneficial effects of nickel arise from the increase in stacking fault energy. The proposed role of dislocations is in accord with that conclusion.

Nitrogen Content

Nitrogen has also been observed to have an influence on the resistance to stress corrosion of austenitic stainless steels. Although nitrogen probably does not directly affect the stacking fault energy, increased nitrogen content tends to promote local order in the alloy.(13) Ordering, as well as low stacking fault energy, tends to restrict slip in the material. Thus, an increase in nitrogen content should lower the resistance of the material to stress cracking.

Second-Phase Precipitates

The influence of second-phase precipitates on transgranular stress corrosion susceptibility has not been well established; however, second-phase particles are known to be effective blocks to dislocation movement. Because dislocation movement is essential for stress corrosion to proceed by the proposed mechanism, a fine dispersion of second-phase particles should increase the resistance to stress corrosion cracking; however, inclusions at the surface may provide local stress concentrations, causing rupture of the protective film and allowing corrosion to occur.

Impurity Content

Impurities segregated to defects usually increase the chemical reactivity in those regions. Therefore lowering the trace impurity content should improve resistance to stress corrosion cracking.

Deformation Process

Deformation processes that produce unusual dislocation arrangements in the alloy should be beneficial if the new arrangements are not conducive to coplanar dislocation motion. Processes such as shock loading and ausforming should be investigated to determine their influences on stress corrosion susceptibility.

CONCLUSIONS

The SRL studies have shown that the role of dislocations in the mechanism of transgranular stress corrosion cracking is to provide a continuous supply of localized anodic regions for selective electrochemical attack. This proposed role indicates that at least two features are necessary for transgranular cracking to occur:

1. Coplanar dislocation movement (thus deformation) must occur during the cracking process.
2. Localized corrosion along specific regions must occur.

Any process or alloy change which promotes cross slip, inhibits dislocation movement, or reduces the tendency for the material to corrode will reduce the susceptibility to transgranular cracking because both of the above are required for cracking to occur.

ACKNOWLEDGMENTS

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REFERENCES

1. R. H. McKane, H. C. Minton, and J. W. Wade. Stainless Steel Failures in Savannah River Plant Areas. USAEC Report DP-539, E. I. du Pont de Nemours and Co., Savannah River Laboratory, Aiken, S. C. (1960).

2. M. R. Louthan, Jr. Stress Corrosion Cracking of Type 304 Stainless Steel - Status Report - March 1, 1964. USAEC Report DP-907, E. I. du Pont de Nemours and Co., Savannah River Laboratory, Aiken, S. C. (1964).

3. M. R. Louthan, Jr. "The Crystallographic Nature of Stress Corrosion Cracking in Type 304 Stainless Steel." Paper presented at the 13th Annual AEC Corrosion Symposium, May 20-22, 1964, Argonne National Laboratory.

4. M. R. Louthan, Jr. "Discussion of Paper 'The Relationship Between Microstructure and Stress Corrosion Failure of High Strength Materials' by P. R. Swann and J. D. Embury." High Strength Materials, edited by U. F. Zachay, John Wiley and Sons, Inc. (1965) (to be published).

5. M. R. Louthan, Jr. Stress Corrosion Cracking of Austenitic Stainless Steel - Status Report - September 1, 1964. USAEC Report DP-957, E. I. du Pont de Nemours and Co., Savannah River Laboratory, Aiken, S. C. (1965).

6. M. R. Louthan, Jr. Initial Stages of Stress Corrosion Cracking in Austenitic Stainless Steel. Paper presented at the 21st Annual NACE Conference, March 15-19, 1965, St. Louis, Mo.

7. A. J. Forty. "Stress Corrosion of α-Brass and Similar Alloys." Physical Metallurgy of Stress Corrosion Fracture. Interscience Publishers, New York, pp 99-120 (1959).

8. W. D. Robertson and A. S. Tetelman. "A Unified Structural Mechanism for Intergranular and Transgranular Corrosion Cracking." Strengthening Mechanisms in Solids. American Society for Metals, Metals Park, Ohio, pp 217-251 (1962).

9. N. A. Nielsen. "The Nature of Initial Corrosion of Stressed Austenitic Stainless Steels." Extended Abstracts of 2nd International Congress on Metallic Corrosion, NACE, Houston, Texas, p 31 (1962).

10. P. R. Swann. "Dislocation Substructure vs. Transgranular Stress Corrosion Susceptibility of Single Phase Alloys." Corrosion 19(3), 102t-112t (1963).

11. S. Barnartt, R. Stickler, and D. Van Rooyen. "Stress Corrosion Cracking Mechanism in Purified 16% Cr-20% Ni Stainless Steels." Corrosion Science 3(1), 9-16 (1963).

12. D. Tromans and J. Nutting. "Electron Microscope Studies of Stress Corrosion Cracking." Fracture of Solids. Interscience Publishers, New York, p 637 (1962).

13. D. L. Douglass, G. Thomas, and W. R. Roser. "Ordering, Stacking Faults and Stress Corrosion Cracking in Austenitic Alloys." Corrosion 20(1), 15t-28t (1964).

14. R. N. Parkins. "Stress Corrosion Cracking." Metallurgical Reviews 9, 201 (1965).

15. J. S. T. van Aswegen and R. W. K. Honeycombe. "Segregation and Precipitation in Stacking Faults." Acta Met. 10, 263-264 (1962).

16. A. A. Hendrickson. "Solute Segregation to Stacking Faults." Acta Met. 10, 901-903 (1962).

17. P. R. Swann. "Dislocation Arrangements in Face-Centered-Cubic Materials and Alloys." Electron Microscopy and Strength of Materials, edited by Thomas and Washburn, Interscience Publishers, New York, p 131 (1963).

18. N. A. Nielsen. "I. Nature of Initial Corrosion of Stressed Austenitic Stainless Steel by Chloride Ions. II. Platinum Decoration of Active Sites." Corrosion 20(3), 104t-110t (1964).

19. A. Rönnquist. "The Influence of Phosphorus on the Stacking Fault Energy and the Sensitivity to Stress Corrosion of Austenitic Stainless Steels." Scandinavian Corrosion Congress, Helsinki, 1964 (pre-print).

20. P. R. Swann and J. D. Embury. "Relationship Between Microstructure and the Stress Corrosion Failure of High Strength Materials." High Strength Materials, edited by V. F. Vackay, John Wiley and Sons, Inc. (1965) (to be published).

21. H. W. Pickering and P. R. Swann. "Electron Metallography of Chemical Attack upon Some Alloys Susceptible to Stress Corrosion Cracking." Corrosion 19(11), 373t-389t (1963).

22. H. W. Paxton, et al. "Stress Corrosion of Single Crystals of Stainless Steels." Physical Metallurgy of Stress Corrosion Cracking, Interscience Publishers, New York, p 181 (1959).

23. R. E. Reed and H. W. Paxton. "Stress Corrosion Cracking of Single Crystals of Some Austenitic Stainless Steels." Metallic Corrosion, 1961, Butterworth and Co., London, p 301 (1962).

24. G. Edmunds. "Season Cracking of Brass." Symposium on Stress Corrosion Cracking of Metals, ASTM-AIME, p 67 (1944).

25. E. E. Denhard, Jr. "Discussion of Paper by J. G. Hines and R. W. Huzell." Physical Metallurgy of Stress Corrosion Cracking, Interscience Publishers, New York, p 223 (1959).

26. C. Edeleanu. "Crack Propagation During Stress Corrosion." Physical Metallurgy of Stress Corrosion Cracking. Interscience Publishers, New York, p 79 (1959).

27. R. P. Jackson. Stress Corrosion Cracking of Austenitic Stainless Steel in Low Chloride Water. Paper presented at 20th Annual NACE Conference, Chicago, Illinois, March 9-13, 1964.

28. D. A. Vaughan, et al. "Relationship Between Hydrogen Pickup and Susceptible Paths in Stress Corrosion Cracking of Type 304 Stainless Steel." Corrosion 19(9), 315t-330t (1963).

29. R. F. Mehl and C. S. Barrett. "Studies on the Widmanstätten Structure, I - Introduction. The Aluminum-Silver System and the Copper-Silicon System." Trans AIME 78, 122 (1931).

30. J. L. English and J. C. Griess. "Stress Corrosion Cracking of Austenitic Stainless Steel in Uranyl Sulfate Solutions." Corrosion 20(4), 138t-144t (1964).

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Mr. R. G. Erdley, Chief
Patent Branch
Savannah River Operations Office
U. S. Atomic Energy Commission
Post Office Box A
Aiken, South Carolina

April 13, 1966

Dear Mr. Erdley:

REQUEST FOR PATENT REVIEW

Please review for patent matter:

DP-1008, The Role of Dislocations in Transgranular Stress Corrosion Cracking of Austenitic Stainless Steels, by M. R. Louthan, Jr.

If any technical clarification is needed please call J. E. Beach whose document review is attached.

Please telephone your comments to the TIS Office (Ext. 3402) and notify me by signing and returning to TIS the original of this letter. A copy is provided for your file.

If you decide to pursue a patent on any development covered, I shall be happy to supply additional information required such as appropriate references and the names of persons responsible for the development.

The above item is approved
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RG. Erdley 4-14-66
R. G. Erdley, Chief Date
Patent Branch
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Very truly yours,

C. W. J. Wende, Director
Technical Division

By: JE Beach
J. E. Beach

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JUL 26 1966

C. W. J. WENDE, DIRECTOR
TECHNICAL DIVISION - AED
EXPLOSIVES DEPARTMENT
WILMINGTON

DP-1008, THE ROLE OF DISLOCATIONS IN TRANSGRANULAR STRESS CORROSION CRACKING OF AUSTENITIC STAINLESS STEELS

by M. R. Louthan, Jr.

This is the third in a series of progress reports that describe the work at the Savannah River Laboratory on the mechanism of stress corrosion cracking in austenitic stainless steels. The previous reports, both by M. R. Louthan, Jr., are DP-907 and DP-957.

On the basis of the experiments and observations described in this and the previous reports, we conclude that stress-corrosion cracking begins with dislocation movement along $\{111\}$ planes. This movement ruptures the protective oxide film on the surface of the metal and allows localized anodic dissolution to occur. This anodic attack then develops into the familiar transgranular stress corrosion crack.

The complete explanation of stress corrosion cracking is undoubtedly more complicated than the description in the attached report. Nevertheless, the suggested role of the dislocations is sufficiently important and complete to be published at this time.

P. H. Permar

P. H. Permar, Research Manager
Nuclear Materials Division

EXTERNAL RELEASE OF TECHNICAL INFORMATION

Description of Material No. DP-1008 Date: 4/13/66

Title: **The Role of Dislocations in Transgranular Stress Corrosion Cracking of Austenitic Stainless Steels**

Author: **M. R. Louthan, Jr.**

Type of Material

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Approved by /s/ P. H. Permar Date: 3/8/66

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R. G. Erdley: 4/14/66

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MEMORANDUM

TO: S. W. O'REAR

FROM: J. E. BEACH

DOCUMENT REVIEW

Document: Report DP-1008

Title: The Role of Dislocations in Transgranular Stress Corrosion Cracking of Austenitic Stainless Steels
Author: M. R. Louthan, Jr.

Contractual Origin: AT(07-2)-1

Present Classification: Unclassified

References:

No items were noted that, in my opinion, should be called to the attention of the AEC for patent consideration.

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