APPENDIX

BIBLIOGRAPHY AND ABSTRACTS ON STRESS-CORROSION CRACKING OF STAINLESS STEEL, 1935–1957

BY ROBERT M. FULLER,[1] GEORGE T. PAUL,[1] AND ALBERT J. MARRON[1]

In addition to stress corrosion proper, the embrittlement of chromium steel is included in the subject matter covered. Distinction is drawn between the two processes in some articles.

This bibliography would appear to present an imposing array of evidence against the use of stainless steel. It cannot be emphasized too clearly, however, that such failures occur primarily in the chemical industry where a relatively small percentage of the stainless steel is used. Even in the chemical industry, failures by stress-corrosion cracking are relatively rare. The rapid progress of such attack and the serious nature of the consequences of such failures are responsible for the present concentration of attention being paid to this subject.

1935

(1) E. S. Dixon, "Petroleum Refineries," The Book of Stainless Steels (E. E. Thum), Am. Soc. for Metals, Cleveland, Ohio, Chapter 18, pp. 581–594, Second Edition (1935).

Cracking of 18 chromium-8 nickel stainless steel under tensile stress is reported in tubes installed in heaters, heat exchangers and condensers. Media described as causing the cracking are water (kind unspecified) at 70 to 120 F and cracked naphtha at 110 to 120 F.

(2) P. D. Ffield, "Airship Construction," The Book of Stainless Steels, (E. E. Thum) Am. Soc. Metals, Cleveland, Ohio, pp. 679–686, Second Edition (1935).

Certain analyses of straight chromium steel are subject to stress corrosion in salt spray or in sea water. Many modifications from 12 to 16 per cent chromium have been tested in the Goodyear-Zeppelin laboratory and found without exception to stress-crack. The necessary stress levels differ. Ground surfaces accelerate the cracking, while a pickled surface is somewhat less susceptible. In construction of the British airship R-101 the 13 per cent chromium steel was heat-treated after fabrication as follows: heated to 1800 F., then air-cooled below the upper critical point, then water-quenched, then reheated to 800 F. Tension was maintained on the tube during the entire treatment.

1936

(3) E. J. Kennedy, Jr., "Transcrystalline Disintegration of 18-8 Steel," *Mining Metallurgist*, Vol. 17, p. 159 (1936).

Stress-corrosion cracking of 18-8 stainless tubes in acid-treated naphtha and clay-treated naphtha, reported by H. M. Wilten.

[1] Corrosion Engineering Section, Development and Research Division, The International Nickel Co. Inc., New York, N. Y.

1939

(4) S. L. Hoyt and M. A. Scheil, "Stress-Corrosion Cracking in Austenitic Stainless Steels," *Transactions*, Am. Soc. Metals, Vol. 27, pp. 191–226 (1939).

A summary is given of the results of a series of corrosion tests made on different types of austenitic stainless steels. The authors discuss the use of a new test which they have employed to determine the stress-cracking tendencies of the austenitic stainless steels. The test combines heat treatments which may arise from the necessity of heating, forming and welding with stress which may be present in equipment fabricated from these alloys.

Actual formation of open cracks in chemical equipment was studied and laboratory stress-corrosion tests made to duplicate the conditions of service bearing on this tendency toward cracking. Stress-corrosion cracking is shown to be intergranular in nature with the steel stressed and subjected to suitable corrosive conditions, although the susceptibility to intergranular attack is not always sufficient to produce cracking.

The variable behavior is discussed and believed to be due to some quality a characteristic of the steel in the as-received condition. The authors failed to produce stress-cracking in stabilized alloys or with properly quenched austenitic stainless steels.

(5) E. E. Thum, "Critical Points," *Metal Progress*, Vol. 36, p. 156 (1939).

Stress-corrosion appearance in stainless steel is described, and several published descriptions mentioned. It is quoted that all varieties of the 300 and 400 series stainless steels must be promptly annealed after heavy cold working, else acid fumes from pickling tanks may cause wholesale cracking.

1940

(6) J. C. Hodge and J. L. Miller, "Stress-Corrosion Cracking of Austenitic Chromium-Nickel Steels and Its Industrial Implications," *Transactions*, Am. Soc. for Metals, Vol. 28, March, 1940, pp. 25–82.

A number of service failures of austenitic stainless steels occurred as result of the formation of localized cracks. Investigation disclosed that the failures involved a condition of internal static stress and exposure of the stressed material to certain corrosive media, which in some cases were so inactive that they left ordinary carbon steel unaffected. The failures were identified as the stress-corrosion type and closely allied to "season cracking" of certain brasses and to the less frequent stress-corrosion cracking in other metals, for example, caustic embrittlement of boiler plate. It was determined that such stress-corrosion cracking in the austenitic chromium-nickel steels may manifest itself either as an intercrystalline or as a transcrystalline failure. Factors which include the stress intensity, strength of the corrosive medium and susceptibility of the material to intercrystalline corrosion determine the path of the failure. Stabilizing elements, such as titanium and columbium, were found ineffective in preventing transcrystalline stress-corrosion cracking, but intercrystalline susceptibility was absent and a somewhat higher stress value was required. To eliminate the possibility of stress-corrosion failure, fabricating stresses must be removed by an elevated temperature treatment and the material slowly cooled to prevent thermal stressing. The evidence indicates that even such heat treatment is ineffective when two metals having different coefficients of thermal expansion, such as 18-8 and carbon steel, are joined by welding. Corrosive media capable of producing stress-corrosion cracking in the austenitic chromium-nickel steels are limited in number. The mixture of ethyl chloride and water was found to be effective in producing stress-corrosion failure of thermowells; anhydrous ethyl chloride was not. Ferric chloride and mercuric chloride solutions were also found to have a damaging effect. It is argued that the mechanism of stress-corrosion failure is similar to that of corrosion-fatigue cracking.

Discussion followed by Wilten, Steckel, Scheil, Brooks, White, Upthegrove, Aborn. Wilten reported failure of a type 18-8 lining exposed at 460 to 500 F (240 to 260 C) to a lubricating oil distillate containing sodium hydroxide. Brooks suggested that surface notches or pits, as formed in stainless by chloride, should increase susceptibility to cracking by reducing the over-all stress necessary to cause initial cracking.

1942

(7) H. J. Rocha, "Spannungskorrosion austenitischer Stähle (Corrosion of Austenitic Steels Under Stress," *Technische Mitteilungen Krupp, Forschungsberichte*, Vol. 5, No. 1, pp. 1–14, (1942).

Details are given on two solutions for testing austenitic steels for propensity to corrosion under stress.

Steels with 18 per cent chromium were studied for effect of carbon and nickel (7.6 to 12 per cent) contents, and of cold working and structure (proportions of ferrite, martensite and carbide) upon corrosion under stress in these solutions.

The nature of cracks (inter or intragranular) and their causes are discussed.

(8) H. J. Rocha, "Stress-Corrosion of Austenitic Stainless Steels; Review of Current Literature," *Stahl und Eisen*, Vol. 62, Part 2, pp. 1091–1094 (1942).

Failures in service do not necessarily correlate with laboratory test results. True stress corrosion is the type which produces transcrystalline cracking in homogeneous gamma solid solutions. Sensitivity of steel is defined as the variety of conditions to which it is susceptible. The physical condition of the austenite and the susceptibility to stress corrosion are affected adversely by tensile stress, cold deformation, and supersaturation of the austenite as shown by the constitution diagram. Contradictory behavior is mentioned where a 19 chromium-7.5 nickel steel, containing about 4 per cent ferrite, did not stress crack in calcium chloride solution. The effect of carbon content and of martensite on cracking is also discussed. The latter is dependent on the ability of the test solution to selectively attack the martensite in the presence of austenite.

To test type 18-8 stainless steel, Carius used a mixture of 40 to 60 parts calcium chloride in 60 to 40 parts of water to which $\frac{1}{10}$ to 1 per cent mercuric chloride was added as an accelerator. Many irregularities in service did not correlate with the test results. Usually cold deformation increases the sensitivity but in other cases the opposite is true and so far has not been explained. Also, the start and path of the cracks appear to be arbitrary. To establish a common viewpoint, the metallurgical and electrochemical factors must be considered. It is suggested that a stress-produced martensitic transformation provides the anodes for electrolytic stress corrosion.

1943

(9) M. A. Scheil, O. Zmeskal, J. Waber, and F. Stockhausen, "First Report on Stress-Corrosion Cracking of Stainless Steel in Chloride Solutions," *Welding Journal*, Am. Welding Soc., Vol. 22 (Supplement), Vol. 8, pp. 493s–504s (1943).

Tests were conducted to select a test solution which would indicate the susceptibility of stainless steel to transgranular cracking, corresponding to the Strauss test solution used to indicate susceptibility to intergranular corrosion. Details of the investigation and test procedures used are covered.

Stainless steels tested were types 302, 304, 309, 316, 317, 321, 329, 347, 403, 410, and 430. Of various chloride solutions, boiling 40 per cent magnesium chloride plus hydrochloric acid to pH 4 had the most favorable characteristics, and was recommended for further study.

(10) M. A. Scheil, O. Zmeskal, J. Waber and F. Stockhausen, "Addendum to First Report on Stress-Corrosion Cracking of Stainless Steel in Chloride Solutions," *Welding Journal*, Am. Welding Soc., Vol. 22 (Supplement), Vol. 8, pp. 504s–506s (1943).

Preliminary tests on columbium stabilized steels to determine the threshold stress below which transgranular cracking will not occur are described. Type 316 (stabilized with columbium) and type 347 alloys were tested. Specimens were stressed at 20, 30, 70, and 90 per cent of the yield point, respectively, and tested for a 24 hr period in boiling 60 per cent hydrated magnesium chloride acidified to pH 4 with hydrochloric acid. One series of alloys was given a stabilizing heat treatment at 1600 F and another series of alloys annealed at 1900 F.

The molybdenum bearing type 316 stabilized with columbium did not stress crack in this test solution at any stress level. Type 347 alloy cracked within 24 hr at stresses as low as 20 per cent of the yield point. The results are tabulated and micrographs of structures obtained are included.

1944

(11) H. Bennek, "Spannungskorrosionerscheinungen bei Eisenlegierungen," (Stress-Corrosion Phenomena in Iron Alloys), *Korrosion u. Metallschutz*, Vol. 20, pp. 133–141 (1944).

Stress-corrosion phenomenon and the form it takes in iron alloys, as related to structure of the material, corroding medium, degree of stress, and the characteristics of the steel is discussed. Stress-corrosion cracking has been observed in stainless steel employed in concentrated alkaline solutions such as sodium hydroxide. The data presented on austenitic, ferritic-pearlitic, and martensitic steels lead to the conclusion that trans- and inter-crystalline stress corrosion are attributable to the same basic cause. Chlorinated organic compounds which may cause attack in the aqueous state include aniline hydrochloride, chloroform, carbon tetrachloride, and ethylene dichloride.

(12) M. A. Scheil and R. A. Huseby, "Studies on Stress-Corrosion Cracking of Austenitic Stainless Steels Types 347 and 316," *Welding Journal*, Am. Welding Soc., Vol. 23 (Supplement), Vol. 9, pp. 361s–365s (1944).

To check the claim by Riedrich that 18-8 stainless steels containing ferrite are much more resistant to cracking in boiling calcium chloride solution than the wholly austenitic alloys, several heats of columbium stabilized 18-8 and 18-8 molybdenum (type 316 and 317) were tested in boiling calcium chloride and magnesium chloride solutions. Test procedures, results and photomicrographs are given. Type 317, with an appreciable amount of ferrite, will not crack in 42 per cent calcium chloride, while types 347 and 316 will show cracking. All types cracked in about the same time in magnesium chloride solutions boiling at 154 C, although the cracking was most severe in type 347 and least severe in type 317. A magnesium chloride solution reported in a reference failed to crack 18-8 molybdenum steel but the salt used in the present experiment cracked many heats at stresses between 10,000 and 80,000 psi as well as types 347 and 304 stainless steels when annealed and stressed elastically. A 42 per cent calcium chloride plus 0.1 per cent mercuric chloride solution was found to be a poor test medium due to pitting attack. Typical stress-corrosion cracking of types 316 and 317 tested in calcium chloride plus mercuric chloride and cracking of type 317 in mercuric chloride are shown photomicrographically. All cracks were transcrystalline.

(13) J. T. Waber, "Stress-Corrosion Cracking of Mild and Stainless Steels," Thesis in Metallurgy, Illinois Institute of Technology (1944); *ASM Metal Literature Review*, Vol. 1, pp. 80–81 (1944).

The author evolves a general theory in which stress-corrosion susceptibility is correlated with the ease of transformation from a metastable state, such as in age hardening. In the cracking of boiler plate steels, heat treatment and stress level were found to be interrelated, and remedial treatments also were studied. The mutual effect of the carbon, nitrogen, and aluminum contents were investigated. Effectiveness of a number of the consequences of theory were verified with magnesium base alloys.

1945

(14) A. M. Bounds, "Stress-Corrosion Cracking of Tubing," Symposium on Stress-Corrosion Cracking of Metals, Am. Soc. Testing Mats., and Am. Inst. Mining and Metallurgical Engrs., p. 471 (1945). (Issued as separate publication *ASTM STP No. 64*.) O. B. J. Fraser, Discussion of Stress-Corrosion Cracking of Nickel and Some Nickel Alloys, *Ibid.*, pp. 458–469.

Stainless steel tubing fails rather frequently under stress corrosion conditions due to the method of manufacture. Plug-drawing and rod drawing produce different

stress patterns, and sinking and straightening operations complicate these patterns. Multi-axial stresses cause the most trouble since stress corrosion is more frequent and severe when torsion or shear stress is combined with other stresses. Stress corrosion is the rule rather than the exception in a control instrument which uses a hard-drawn stainless tube subjected to torsional loads. Type 347 stainless tubing, hard-drawn, has failed in kerosine containing one half per cent sulfuric acid.

During the discussion, Fraser mentioned that tubes intended for service under conditions known to be conductive of stress-corrosion cracking should have at least a partial stress-relief anneal before or after being fabricated into equipment.

(15) O. B. Ellis, "Some Examples of Stress Corrosion Cracking of Austenitic Stainless Steel," Symposium on Stress-Corrosion Cracking of Metals, Am. Soc. Testing Mats. and Am. Inst. Mining and Metallurgical Engrs., p. 421 (1945). (Issued as separate publication *ASTM STP No. 64.*) Discussion, p. 425.

Six failures of stainless steel by stress-corrosion cracking were examined in the American Rolling Mill Co. research laboratories. These occurred in coffee urns, wool conditioning units, a dyeing machine and a steam-jacketed stock pot. In each case the equipment failed in a comparatively short time after exposure to conditions of high humidity at temperatures in the range of 100 to 200 F. All failures were characterized by general embrittlement and cracking of the stainless steel, with only slight indications of general corrosion except at cracks. Composition of the steels and results of microscopic examination are given. Stainless steel has been used successfully for thousands of similar applications, and the number of failures of this kind has been very small. Discussion by Feild, LaQue.

(16) R. Franks, W. O. Binder, and C. M. Brown, "The Susceptibility of Austenitic Stainless Steels to Stress-Corrosion Cracking," Symposium on Stress-Corrosion Cracking of Metals, Am. Soc. Testing Mats. and Am. Inst. Mining and Metallurgical Engrs., p. 411 (1945). (Issued as separate publication *ASTM STP No. 64.*) Discussion p. 425.

Corroding media were examined from the standpoint of promoting susceptibility to stress-corrosion cracking in the annealed and cold-rolled austenitic chromium-nickel steels. Only a few of the corrodents have been found to cause this type of failure. Corrosive media that most readily produce stress-corrosion cracking are listed.

In discussion by Scheil, Feild, Weber, LaQue, Davis, Krivobok, the infrequency of stress-corrosion cracking was brought out. Davis reported that metal (chromium-11 to 12 per cent nickel-columbium stabilized, exposed to condensate containing not more than 18 ppm chloride) having a grain direction or rolling direction parallel to the bend was found to be much more susceptible than with the direction perpendicular to the bend. The former cracked within four hours, the latter was uncracked after 50 days.

(17) R. B. Mears, R. H. Brown, and E. H. Dix, Jr., "A Generalized Theory of Stress Corrosion of Alloys," Symposium on Stress-Corrosion Cracking of Metals, Am. Soc. Testing Mats. and Am. Inst. Mining and Metallurgical Engrs., p. 323 (1945). (Issued as separate publication *ASTM STP No. 64.*) Discussion, p. 340.

Data obtained at the Alcoa Research Laboratory and further theories on stress corrosion are presented. Considerable data deals with aluminum alloys but alloy steel, stainless steel, copper, magnesium, platinum, and gold alloy systems are also mentioned. A table lists corrosion environment in which stress corrosion has occurred for these alloys, with references. Causes of localized attack, a technique for electrochemical measurement between grain and grain boundaries, effect and nature of stress, directional effects, stress-relief, and cathodic protection are discussed. Corrosion in most cases occurs by an electrochemical mechanism. Anodic and cathodic characteristics vary with the nature of the corroding environment. Grain boundaries of pure aluminum sheet when quenched in cold water are anodic but become cathodic when slowly cooled. Corrosion of copper-zinc-nickel alloy in ammonia, of iron-chromium-nickel-carbon and iron-chromium-nickel-molybdenum-carbon alloys in sulfuric acid plus copper sulfate and of silver-platinum in ferric chloride solutions is mentioned.

(18) J. H. G. Monypenny, "Stress-Corrosion Cracking of 18-8," *Metal Progress*, Vol. 48, pp. 1119–1120 (1945); Discussion, Vol. 49, p. 563 (1946).

Examples of stress-corrosion cracking of austenitic stainless steels in mildly corrosive environments are cited. One case is that of a severely strained 18-8 stainless hospital bowl, which was drawn from polished sheet and a beaded edge turned over. No intermediate or final softening was given, and the final product was in a drastically cold worked condition. Tests with hydrochloric acid suggest that cracking of 18-8 might occur in cold-rolled material with a tensile strength of 200,000 psi or more, but none occurred when tensile strength was less than 180,000 psi, even when material was subjected to externally applied stress while immersed in test liquor. The failure of the bowl indicates the wisdom of softening deep-drawn articles of 18-8 as soon as possible after drawing, and of the danger which may result from using 18-8 in heavily cold-drawn condition for aircraft structure. The British specification for cold-rolled 18-8 sheet or strip for aircraft construction limits the tensile strength to 157,000 psi.

(19) M. A. Scheil, "Some Observations of Stress-Corrosion Cracking in Austenitic Stainless Alloys," Symposium on Stress-Corrosion Cracking of Metals, Am. Soc. Testing Mats. and Am. Inst. Mining and Metallurgical Engrs., p. 395 (1945). (Issued as separate publication *ASTM STP No. 64.*) Discussion, p. 425.

Stress-corrosion cracking of austenitic stainless alloys may occur under certain corrosion environments irrespective of their susceptibility to intergranular corrosion.

Test samples are described for investigating stress-corrosion susceptibility of alloys for industrial equipment.

A laboratory test using a solution of magnesium chloride boiling at 309 F was found to produce transgranular cracks in several alloys investigated. In types 347 and 316 stainless steel tubing a residual stress of the order of 10,000 psi was observed to initiate cracking.

The susceptibility to stress-corrosion cracking, as judged by the boiling magnesium chloride test, indicates that alloys may be selected which will withstand a high stress in service. The surface finish (whether pickled or polished) is significant.

Stress specimens of stainless alloys included in a corrosion testing program will aid in determining the acceptability of these fabricated alloys, when stressed, to the service conditions.

In discussion by Jasper, Feild, Waber, LaQue, Kornhauser, Mackay, Dietrick, and Krivobok, the infrequency of stress-corrosion cracking was brought out.

(20) R. Sergeson, "Steels for High-Temperature Service," *Industrial Heating*, Vol. 12, No. 7, pp. 1209, 1214, 1230 (1945).

Steels for high-temperature applications are divided into carbon, low alloy, hot-working, semi-stainless, and stainless steels. Resistance to stress corrosion, scaling, creep, and other influences of temperature are considered for each group.

1946

(21) A. De Sy, "The Relation Between Welding and Corrosion of Stainless Steels," *Transactions*, Institute Welding, Vol. 9, No. 2, p. 65 (1946).

Corrosion is examined with reference to stainless steels. Intergranular corrosion, pitting and stress corrosion are treated in detail.

(22) R. Franks, "Stress-Corrosion Cracking of 18-8," *Metal Progress*, Vol. 49, pp. 563–565 (1946).

The writer does not support the inference made by Monypenny, in correspondence, of Nov. 1945, that cold-rolling austenitic stainless steels to be used in hospital equipment made them more subject to stress-corrosion cracking. Data which show the reverse to be true are presented. In other words, under simultaneous influence of stress and corrosion, the cold-rolled steels will withstand higher stress than the annealed steels. Data on 17-7 and 18-8 stainless steels in magnesium chloride solution previously published are given.

(23) "A note on the Influence of Nitrogen in Steel," British Intelligence Objectives Sub-Committee, Report 898, 6 pp. (*Circa* 1946).

Information was obtained from personnel of Rheinmetall Borsig. For some steels nitrogen is a harmful impurity; in others it is useful and is deliberately introduced during the melting process. Reference is made to nitrogen as a substitute for nickel. The saving in nickel effected by addition of 0.20 nitrogen in 12 per cent nickel-12 per cent chromium steel was accompanied by improved resistance to stress corrosion.

(24) M. S. Fisher and H. Brooks, "Investigation of the Strength of Bronze Welded Joints," *Transactions*, Institute of Welding (London), Vol. 10, No. 5, pp. 149–160 (1947).

Discussion of bronze welding as compared to other methods of welding joints in austenitic stainless steels and other materials. Nickel-chromium steels tend to intercrystalline stress-cracking when bronze-welded and become hardened and brittle. Steels that require heat treatment after welding should not be bronze-welded. The corrosion resistance of austenitic stainless steel is not affected by bronze welding.

(25) L. A. Glickman and V. A. Stepanov, "Stress-Corrosion Cracking of High-Chromium Steel," *Boiler and Turbine Construction* (USSR), Feb. 1947, p. 19.

Failure of 2 steel bushing on the shaft of a turbine caused by stress-corrosion cracking was described and a mechanism proposed.

(26) L. F. Spencer, "The Stainless Steels," *Steel Processing*, Vol. 33, pp. 474–478, 508, 558–563, 584, 624–629, 755–760 (1947).

The introduction classifies types of stainless steel with application, particularly in high temperatures. Creep data are graphed and tabulated and microstructures are shown. Part II covers forging. Tests of relative corrosion resistance, forging specifications, equipment requirements, use of radiation pyrometer, die design, and materials, precautions in general and for individual types of stainless are covered. Photomicrographs show the effect of overheating. The effects of forging at various temperatures, hot rolling and cold drawing of 17.42 chromium-0.05 carbon and 18.24 chromium-0.12 carbon steels on mechanical properties are tabulated. Part III deals with fabrication and heat treatment after cold working. Intergranular corrosion, proper finish for sheet and strip, forming and deep drawing equipment lubricants, annealing and spinning are covered. A table compares the yield, tensile strength, elongation, Olsen cup test, and Rockwell hardness of types 302, 430, and 410 and a deep drawing plain carbon steel. The effect of cold-rolling on type 302, and annealing temperature with kind of cooling for various types of materials are also tabulated. Effect of cold work on tensile strength of types 301, 302, 304, and 316 stainless is graphed. Microstructures show stress-corrosion cracking due to zinc pickup from copper forming tools used in spinning. Part IIIa covers cold heading and also the pickling of austenitic stainless steel compositions. Graphs show optimum concentrations of pickling bath elements and the relationship between metal attack and concentrations of various pickling solutions, and photomicrographs show various structural and other aspects of pickling.

(27) M. H. Springer, E. V. Succop, D. S. McKinney, and M. A. Scheil, "An Attempt to Select a Suitable Specimen for the Study of Corrosion Cracking in 18-8 Steel," *Welding Journal*, Am. Welding Soc., Vol. 26 (Supplement), Vol. 12, pp. 530s–538s (1947).

All specimens tested were type 347 stainless steel and were exposed to a single environment. Tests showed that magnesium chloride, the stress-corrosion medium used, does not cause general corrosion or pitting of most of the stainless alloys. Contamination of the solution over a period of 300 hr did not accelerate corrosion. A variety of permanently deformed specimens were given various stress relieving heat treatments and tested to determine the effect of locked-up stresses and the effectiveness of the heat treatment in eliminating their effect on stress-corrosion cracking. Consideration of the data indicates that corrosion cracking of austenitic stainless steels requires a critical combination of heat treatment, applied stress and corroding environment. Specimens and test results are discussed and illustrated.

(28) L. J. Wieschhaus, "Uses of Shot-Peening Other Than for Fatigue Durability," *Product Engineering*, Vol. 18, No. 8, pp. 122–127 (1947).

Use of shot-peening to inhibit stress-corrosion cracking, to reduce porosity in metal parts subjected to pneumatic and hydraulic pressures, to test the adherence of silver plate, to improve the lubricating properties of plain bearings and to replace polishing operations is discussed. Magnesium alloys, brass and mild and stainless steels were tested.

(29) C. A. Zapffe, and M. E. Haslem, "Acid Composition, Concentration, Temperature and Pickling Time as Factors in the Hydrogen Embrittlement of Mild Steel and Stainless Steel Wire," *Transactions*, Am. Soc. for Metals, Vol. 39, pp. 213–237 (1947); Discussion, p. 237.

Stainless steels 440-C, 410, 431 and SAE steels 1020, 1060, and 1090 were studied in sulfuric, hydrochloric, phosphoric, acetic, hydrofluoric, and nitric acids to determine the effects of composition of metal, thermal treatment, mechanical working, composition of acid solution, concentration of acid, temperature, and pickling time. Inhibitors were not used. Strongly ionized reducing acids (sulfuric, hydrochloric, and hydrofluoric) caused embrittlement over a wide range of acid composition; phosphoric acid and acetic acid caused embrittlement over a narrower range; nitric acid caused embrittlement only in SAE 1020 steel; and nitric hydrofluoric acid mixtures had no embrittling effect.

1948

(30) H. R. Copson, "Stress-Corrosion Cracking," Corrosion Handbook (H. H. Uhlig), John Wiley and Sons, Inc., New York, N. Y., pp. 569–578, 1009–1014 (1948).

The principal factors in stress-corrosion cracking are tensile stress, environment, time, and internal structure. Cracking of stainless steel has been eliminated by a stress-relief anneal at 1350 F for one hour followed by furnace cooling overnight.

There is no universal test of susceptibility to stress-corrosion cracking. Correlation between laboratory tests and service performance is difficult to obtain; exact correlation should not be expected. Laboratory tests may be run with internal or applied stress, and may apply a constant load or operate at constant deformation. Environments used for testing the stress-corrosion cracking tendencies of stainless steel include 10 per cent copper sulfate plus 10 per cent sulfuric acid (Strauss test solution), boiling 60 per cent hydrated magnesium chloride plus hydrochloric acid to pH 4, and boiling 42 per cent magnesium chloride. The latter test environment is now preferred.

(31) M. G. Fontana, "Stress-Corrosion and Corrective Measures," *Metal Progress*, Vol. 53, No. 6, pp. 838–840 (1948).

This part of the chapter on "The Eight Forms of Corrosion," in the third edition of "The Book of Stainless Steels" discusses stress-corrosion manifestation, types of failures, examples of stress corrosion in various metals including stainless steels, and methods of combatting corrosion particularly by improving the design of equipment.

(32) F. H. Keating, "Chemical Manifestations of Internal Stress," Symposium on Internal Stresses in Metals and Alloys, Inst. of Metals (London), pp. 311–331 (1948). Discussion, pp. 465, 473, 483.

The combined effect of internal stress and a corrosive environment is discussed, and significance of this combination, referred to as stress-corrosion cracking, is indicated. Literature on stress-corrosion cracking of commoner industrial alloys, including nickel and 18-8 stainless steel, is reviewed, and examples of such cracking in industrial plant are recorded. Various factors involved in stress corrosion are considered and a tentative explanation of mechanism of such cracking is proposed. Photomicrographs and 97 references are included.

During the discussion, G. A. Dummett cited instances of stress-corrosion cracking of 18-8 in calcium chloride brine in a milk cooler and of a heat exchanger in a vapor mixture of acetic acid, ethyl alcohol, acetaldehyde, and water.

(33) W. P. Rees, "Note on Stress-Corrosion Cracking of Steels in the Presence of Sulfur Compounds," Symposium on Internal Stresses in Metals and Alloys, Inst. Metals Monograph. Report Series No. 5, pp. 333–336 (1948); Discussion, pp. 466, 478.

Reference is made to cases of failures of ferrous materials by stress-corrosion cracking, where the corroding agent was probably hydrogen sulfide or some sulfur-containing compound. Laboratory experiments are referred to which have shown hardened and tempered alloy steels used for gas cylinder manufacture to be susceptible to stress-corrosion cracking in the presence of moist hydrogen sulfide or carbon bisulfide. In tests, both 18-8 chromium-nickel and 12 to 15 per cent chromium steels were cracked in moist hydrogen sulfide.

(34) W. G. Renshaw, "Maintenance of Stainless Steel Equipment in Refineries," Parts I and II, *Petroleum Processing*, Vol. 3, No. 1, Jan., 1948, p. 25; No. 2, Feb., 1948, p. 155.

Part II discusses avoidance of stress corrosion, pitting or localized corrosion, and cleaning and removing coke deposits from stainless materials.

(35) M. A. Scheil, "Stress-Corrosion Cracking in Stainless Alloys," Corrosion Handbook (H. H. Uhlig), John Wiley & Sons, Inc., New York, N. Y., pp. 174–182 (1948).

Stress can cause propagation of cracks intergranularly, transgranularly, or in both manners. Theory and understanding of stress-corrosion cracking do not exist, comparable with intergranular corrosion. Methods of control are only stress-relief annealing and avoidance of stress. The corrosive media responsible cannot yet be defined completely. Aqueous acid chloride solutions appear to be the most active media; acid sulfite cooking liquors and hot caustic soda solutions have been responsible.

(36) H. H. Uhlig, "The Stress-Corrosion Cracking of Iron and Some Ferrous Alloys," *Metals Handbook*, Am. Soc. Metals, Cleveland, O., pp. 233–234 (especially p. 234) (1948).

The transgranular pattern of stress-corrosion cracking of austenitic stainless steels is discussed. Specific solutions in which stress-corrosion cracking has been observed, especially hot chlorides, are listed. Resistance to cracking varies with the nickel content. Ferritic stainless steels are less susceptible.

(37) G. Wassermann, "The Effect of Stress and Temperature in Stress-Corrosion," *Zeitschrift für Metallkunde*, Vol. 39, pp. 66–71 (1948).

S-N fatigue diagrams from previously published data are given for ferritic steels, austenitic stainless steels, brass and aluminum-copper, aluminum-magnesium, aluminum-zinc-magnesium, and magnesium-aluminum-zinc alloys in mild and severe corrosive media for periods up to 4000 hr and temperatures up to 250 C to show a linear relationship between temperature and duration of test period.

(38) C. A. Zapffe and M. E. Haslem, "Sensitivity of Different Steels to Pickling Brittleness," *Wire and Wire Products*, Vol. 23, pp. 563, 609 (1948).

Plain carbon steel, hardenable stainless steels, and nonhardenable stainless (austenitic) alloys were among the materials tested. In cathodic pickling, annealed steel is the least susceptible and hardened steel the most susceptible to embrittlement. Increasing carbon content increases the susceptibility of both hardened and annealed stainless steel. Annealed 410 and 431 stainless steels resist embrittlement, even when cold drawn. In acid pickling, with the exception of type 440-C, the stainless steels are less susceptible to embrittlement than they are in cathodic pickling. Type 410 shows non-susceptibility in all conditions. Type 431 stainless steel shows embrittlement only in the hardened and cold-drawn condition, and then only in dilute sulfuric acid and dilute hydrochloric acid. In phosphoric acid and acetic acid, both 410 and 431 are resistant. Type 440-C stainless steel and 1020 mild steel retain similar relationships in either acid or cathodic pickling. Seven per cent hydrochloric acid is slightly more damaging to 440-C than 10 per cent sulfuric acid but the effect does not appear with 50 per cent hydrochloric acid. All of the acids studied except nitric acid cause similar injury in equal pickling times.

(39) C. A. Zapffe and M. E. Haslem, "Evaluation of Pickling Inhibitors from the Standpoint of Hydrogen Embrittlement," *Wire and Wire Products*, Vol. 23, pp. 933, 1126, 1172 (1948).

Martensitic stainless steels, pickled in 10 per cent sulfuric acid, are severely embrittled in the presence of most pickling inhibitors despite the effectiveness of such inhibitors in reducing hydrogen evolution. Two inhibitors have been specially developed and were said to prevent embrittlement. In cathodic pickling, all inhibitors cause embrittlement.

1949

(40) H. F. Brown and W. M. Goryl, "Corrosion and Stress Factors in Piping Expansion-Joint Failures," *Proceedings*, Am. Petroleum Inst., 14th Mid-Year Meeting, Division of Refineries, Vol. 29M, No. 111, pp. 175–183 (1949).

A satisfactory material for catalytic-cracking unit expansion-bellows construction must be stainless to resist corrosion; it must have a low susceptibility to intergranular attack and stress corrosion; and it should have a high yield and elastic limit. Type 347 was described as meeting these qualifications more completely than any other material considered.

(41) G. T. Colegate, "Shot Peening," *Sheet Metal Industries*, Vol. 26, No. 262, pp. 371–380, 384 (1949).

Shot peening was shown to be effective in preventing, or at least minimizing the risk of season-cracking of brass, and in reducing the stress-corrosion cracking of stainless steel.

(42) F. L. LaQue, "Corrosion Resisting Metals and Alloys," Paper presented before the University of Texas, Short Course in Corrosion Sponsored by Nat. Assn. Corrosion Engrs., Sept. 12–16, 1949, 16 pp.

The following subjects were discussed: Corrosion-resisting metals and alloys including iron, steel, lead and its alloys, copper and it alloys, aluminum; nickel and high nickel alloys, such as Monel, Inconel, Hastelloys; stainless steels; dezincification; intergranular attack; stress-corrosion cracking; corrosion-fatigue; impingement; cavitation-erosion; and crevice corrosion.

(43) C. A. Zapffe and M. E. Haslem, "Hydrogen Embrittlement in Electroplating of: Copper, Cadmium and Zinc, Nickel, Tin and Lead," *Plating*, Am. Electroplaters' Soc., Vol. 36, pp. 906–913, 972 (1949); Vol. 37, pp. 366, 610 (1950).

Metals plated and embrittled include type 440-C stainless steel. It is sensitive to hydrogen embrittlement in almost all of the baths used for electroplating these metals. The dilute fluoborate bath and the conventional Watts nickel bath result in the least embrittlement. Absorption of hydrogen by the cathode is independent of the total amount of hydrogen deposited and, in most of the baths tested, it exceeded the absorption from hydrogen plating alone.

1950

(44) K. Bungardt, "Development and Present Status of Rolled and Forged Stainless Steel," *Stahl und Eisen*, Vol. 70, pp. 582–596 (especially pp. 585–586) (1950).

The present knowledge of stress-corrosion cracking of 18-8 stainless steel can be summarized as follows, with particular attention to the studies of H. J. Rocha: Resistance to stress corrosion increases with austenite stability, which is increased by copper additions of 1 per cent or more; with increasing dissolved carbon in gamma-mixed crystal; with reduced cold working; occasionally in alpha-gamma mixed crystals by the ferrite becoming anodic. Martensite formed by cold work may likewise act as an anode. Intercrystalline stress corrosion is not related to intercrystalline corrosion. Extreme cold-working makes ferritic stainless susceptible. The real causes of intracrystalline stress corrosion are not well known.

(45) G. T. Colegate, "The Corrosion of the Austenitic Stainless Steels," Part I—Types of Stainless Steels, and Forms of Attack; Part II—Pitting and Intergranular Corrosion; Part III—Stress Corrosion. *Acta Metallurgia*, Vol. 41, pp. 147–150, 259–262, 305–308 (1950).

Many factors governing the corrosion of stainless steels are discussed, including the effect of alloying elements and of corrosive media which may contact the material in service. Types of corrosive attack are reviewed and include stress corrosion. Modified compositions and atmospheric exposure are also reviewed.

(46) F. W. Davis, "Stress-Corrosion in a Stainless Steel Compressor," *Transactions*, Am. Soc. Metals, Vol. 42, pp. 1233–1250 (1950); Discussion, p. 1251.

The failure of a stainless steel turbo-compressor by stress corrosion of two rotors is discussed. The unit was used to compress steam which was subsequently condensed for use in a chemical process requiring high purity water. Both the raw water supply and leachings from parts of the failed unit contained chlorides, but the condensate contained less than one-half ppm of total solids. Excessive dynamic stresses were imposed on all rotors by unbalance caused by erosion of unequal lengths from the vane tips. Two rotors failed completely by transcrystalline cracking and one side only of each of the adjacent rotors contained pronounced stress patterns of incipient transcrystalline cracks. No evidence of corrosive attack could be detected on the inside surface of the compressor casing except in the two stages where rotor failure had occurred and where a decided strain pattern indicated the presence of a fluid at least mildly corrosive. Data from a second compressor, which operated under identical conditions with no evidence of similar stress corrosion, are included for comparison.

(47) U. R. Evans, "Corrosion Cracking (Fracture due to Stress Corrosion)," Symposium on The Fracture of Metals, The Institution of Metallurgists, London (England), pp. 68–100 (1950).

A theoretical exposition-part of a refresher lecture course. Austenitic stainless steel and magnesium chloride solution are mentioned.

(48) J. J. Harwood, "The Influence of Stress on Corrosion," *Corrosion*, Nat. Assn. Corrosion Engrs., Vol. 6, pp. 249–259, 290–

307 (especially pp. 303, 304) (1950); Discussion, p. 389 (1950) Discussion, Vol. 7, p. 109 (1951).

The effects of stress on the internal structure and energy characteristics of metals are discussed with relationship to their influence on corrosion reactions. The nature and importance of residual stresses and the non-homogeneity of worked metals are emphasized. Recent concepts of the nature of grain boundaries are reviewed and their importance in reactions where stress and corrosion act in a conjoint manner is described. Stress corrosion of alloys is discussed and the influence of metal composition and structure, environment, state, and degree of stress and methods of prevention are presented. The oxide film, mechanical and electrochemical theories of stress-corrosion cracking are reviewed and it is shown that the experimental evidence favors an electrochemical mechanism. Stress corrosion of stainless steels is discussed.

(49) R. A. Huseby and M. A. Scheil, "Corrosion and Corrosion Testing in the Pulp and Paper Industry," *TAPPI*, Vol. 33, No. 3, pp. 138–148 (1950).

General corrosion, pitting, intergranular attack, stress-corrosion cracking, galvanic corrosion, dezincification, and erosion are discussed with application to stainless steel in the pulp and paper industry.

(50) F. J. Lambert and C. Coughlen, "Investigation of Failure of Type 347 Stainless Steel Tank for Lithium," U.S. Atomic Energy Commission, Y-694, 22 pp. (1950).

An investigation revealed that a stainless steel tank failed because of internal stress and carbide precipitation. The primary cause of failure was due to internal stresses located at the surface of the weld metal-parent metal junction.

(51) F. L. LaQue, "Report on Round Table Discussion on General Corrosion Problems," *Corrosion*, Nat. Assn. Corrosion Engrs., Vol. 6, No. 10, p. 327 (1950).

The following was among the questions submitted, and answers given at a discussion session during the Sixth Annual Conference, National Association of Corrosion Engineers, St. Louis, Mo., April 4 to 7, 1950:

Question: "We would appreciate a discussion of unpublished data regarding the tendency of austenitic stainless steels to fail by stress corrosion when in contact with hot brackish water."

Answer: "One refinery lost a type 304 stainless steel tube bundle due to stress corrosion cracking after six days operation handling a cooling water containing about 1700 ppm chlorides. The cracks were about 4 to 6 in. from the end of each tube sheet. It was fairly well determined that the stresses were concentrated at these locations due to bouncing of a bundle during a truck shipment of 70 or 80 miles from the manufacturer to the user. Difficulties are most likely to occur where there is a chance for surfaces under stress to reach temperatures high enough to effect an appreciable concentration of the chlorides in the cooling water—as in the case of cascade coolers handling hot gases within the tubes."

(52) H. Nathorst, "Stress-Corrosion of Stainless Steels. I. Practical Experiences. II. An investigation of the Suitability of the U-Bend Specimen," *Jernkontorets Annaler*, Vol. 134, pp. 97–133 (1950); *Welding Research Council Bulletin*, No. 6, Oct. 1950, 18 pp.

I. An inventory of specific experiences of stress-corrosion cracking of 18-8 stainless steel encountered by members of the Swedish Ironmasters' Association. Environments included chloride (sodium chloride, calcium chloride, zinc chloride, sulfite waste liquor and wash), steam and hot water, sodium hydroxide, black liquor, diphenyl-diphenyl oxide, severe industrial atmosphere, sodium hypochlorite, orthodichlorobenzene, pickling baths. A number of environments described in the literature are noted.

II. A report of an investigation of the reproducibility of results obtained with strips made into U-bend specimens and exposed to calcium chloride solutions. There was used an 18.1 chromium-8.3 nickel stainless steel, cold rolled, annealed, pickled and passivated, but not straightened. Reproducibility was so poor that the test was considered as qualitative only. Calculations are quoted for stress values at different points of a U-bend specimen, taken from Mailänder.

(53) M. T. Simnad, "A Review of the Electrochemistry of Stressed Metals," *Journal*, Electrochemical Soc., Vol. 97, No. 2, pp. 31C–44C (1950).

A critical survey of published work on the electrochemistry of metals covers origin and nature of internal stresses, latent energy in deformed metals, influence of stress on electrode potential and corrosion rate, effect of surface preparation on corrosion, stress corrosion of non-ferrous and ferrous metals, corrosion fatigue, and internal stress in electrodeposited metals. Stainless steels are considered. 126 references.

(54) H. Thielsch, "Physical Metallurgy of Austenitic Stainless Steels," *Welding Journal*, Am. Welding Soc., Vol. 29 (Supplement) Vol. 15, pp. 577s–621s (especially pp. 600s, to 603s) (1950).

The present knowledge and the results of recent research on chromium-nickel stainless steels and their weldability are reviewed. Metastable austenite, ferrite, and sigma in chromium-nickel stainless steels, carbides, corrosion resistance, crack sensitivity, stress-corrosion cracking, shrinkage, distortion and restraint, grain size, the effects of cold deformation, subzero and elevated temperatures are discussed.

The susceptibility of wrought and welded stainless steels to stress-corrosion cracking depends upon (1) stresses in the steel, (2) the action of the corroding agent, (3) plastic deformation of the steel, (4) physical characteristics of the alloy and (5) length of exposure to corroding solution. Their effects are discussed, together with the effect of austenite stability and of alloying elements.

Treatments to reduce this susceptibility are lowering the crack sensitivity of the stainless steels itself, suitable heat treatments that reduce the residual stresses, and adjustment of composition, particularly by the addition of molybdenum. It is likely that many of the failures in wrought and particularly in welded stainless steels, which are now either overlooked or ascribed to other effects, are caused by stress-corrosion cracking.

(55) W. Tofaute and H. J. Rocha, "Corrosion of Austenitic Steels under Tension," *Instituto del Hierro y del Acero* (Spain), Vol. 3, pp. 101–110 (1950).

The difference between stress corrosion and intergranular corrosion and testing problems are discussed. Time-to-rupture in relation to nickel and chromium contents is shown. The effects of ferrite and martensite on stress corrosion are described. Stress corrosion can be avoided if the austenite is stable and is associated with quantities of ferrite so as to form local cells to impede corrosion.

(56) W. Tofaute and H. J. Rocha, "Stress-Corrosion Cracking in Stainless Steels," *Técnica Metalúrgica* (Barcelona) (Spain), Vol. 6, No. 56, pp. 427–434 (1950).

Various types of corrosion in stainless steels, especially that due to stress-corrosion cracking are considered. Results of tests of steels containing 18 to 19 per cent chromium and 8 to 12 per cent nickel are given.

It is suggested that there is a connection between stress corrosion and the alpha-gamma transformation which takes place on straining austenitic steels. Cold working can either slow or speed the rate of cracking failure.

(57) H. H. Uhlig, "Action of Corrosion and Stress on 13 Cr Stainless Steel," *Metal Progress*, Vol. 57, p. 486–487 (1950).

Strips of 12.5 chromium-0.1 nickel-0.12 copper-1.2 silicon stainless steel were U-bent and immersed in 3 per cent sodium chloride. Rusting and pitting soon occurred but cracking occurred only after 4½ months. One specimen, stressed as above, was coupled to a sheet of aluminum foil and submerged in the salt solution. With this arrangement, the stainless steel strip cracked overnight, thus suggesting that cathodic polarization was the critical factor causing rapid failure. When a platinum anode was used in a salt solution cell with the stressed specimens as cathodes, the specimens cracked. Using dilute sulfuric acid containing a few drops of white phosphorus dissolved in carbon disulfide to accelerate hydrogen adsorption by the alloy, cracking again occurred. These experiments suggest that so-called stress-corrosion cracking of this martensitic type stainless steel may occur under any conditions that favor discharge of hydrogen ions on the surface. Specimens are exceedingly brittle after brief cathodic polarization in sodium chloride or sulfuric acid but the usual ductility is regained on standing in air. Failure by cracking of the stressed martensitic stainless steels exposed to a corrosive environment may probably best be described as hydrogen embrittlement.

(58) J. T. Waber and S. Waber, "Accelerated Corrosion Test of Nickel-Based Alloys and Steels," *U. S. Army EC Report LA-1313*, Los Alamos Scientific Laboratory, Los Alamos, N. M. (1950).

Tests were made to select a material of construction for ductwork carrying mineral acids in a laboratory having radioactivity hazards which made leakage intol-

erable. Although its general corrosion rate was not the lowest of the alloys tested, Inconel was preferred because of its unique freedom from stress-corrosion cracking and pitting.

Stress-corrosion tests were run on seamless and welded stainless steel tubing in the standard magnesium chloride reagent. The samples cracked abundantly after a few hundred hours. Considerable protection was afforded by heat-treating the tubing at 1950 F for ½ hr and then air-cooling.

Where stainless tubing is used for drains, the 1950 F heat treatment is recommended. It is also desirable that the steel be pickled before being passivated.

(59) G. H. Wray, "Stress Corrosion on Radial-Flow Steam Turbines," *Engineering*, Vol. 169, pp. 141, 169 (1950).

This work includes a summary of a metallurgical investigation on cold-work effects of rolling the dovetail blade fixture, during manufacture of blade rings for Brush Ljunstrom double rotation turbines. An earlier method of construction, now superseded, involved securing some of the blades in such a manner as to require cold-deformation of the steel. Ring dovetails were closed onto individual blades. Original Ljunstrom machines were fitted with blade rings having welded-blade construction throughout the radial-flow system; these gave satisfactory performance. Subsequently, a new type of blade ring was introduced in which the rings were built up of individual blades of nickel-chromium-molybdenum steel (change necessitated by increased stresses to which blade roots were subjected in larger-diameter blade rings for machines of higher output). Difference between welded and individually-bladed construction is illustrated. Rings of welded-blade construction were 5 per cent nickel steel. It is stated that use of welded blading has been continued in production of smaller-diameter blade rings. Account of examination of sections cut from damaged nickel-chromium-molybdenum steel blade rings and of laboratory investigations is given.

(60) Conference on Stainless Steels, Vestnik Akademii Nauk (S.S.S.R.), Vol. 20, Aug. 1950, pp. 66–71. (In Russian.)

A brief review of sixteen reports presented at the above conference, including stress-corrosion cracking.

1951

(61) C. L. Bulow, "Duplex Tubing For Use In The Petroleum Industry," *Petroleum Engineer*, Vol. 23, No. 10, pp. C5–C8 (1951).

Applications of duplex tubing as a solution to dual corrosion problems. Stainless tubes have failed from transcrystalline stress-corrosion cracking in contact with certain cooling waters. Where cracking has occurred from the outside in atmospheric coolers copper alloy-clad stainless tubes have been used. Stainless steel-clad copper tubes are being used to withstand corrosion by impinging high velocity vapors. In coolers handling amines and mixtures containing amines, low-carbon steel lined with Admiralty and various cupro-nickel alloys and aluminum brass have performed satisfactorily, particularly where gulf or bay waters are used for cooling. 70/30 and 80/20 cupro-nickel, aluminum brass and bronze, and Admiralty brass are usually combined with steel where sea water is used for cooling ammonia. Duplex tubing is finding increasing use in condensers, heat exchangers and coolers for handling numerous corrosive gases where the general or impingement corrosion resistance of low carbon, chromium or stainless steel, tin, Monel, aluminum, nickel and lead combined with copper alloys are required. Illustrations.

(62) D L. Horigan, "Corrosion-Resistant Metals for the Pulp and Paper Industry," *Paper Trade Journal*, Vol. 133, No. 14, pp. 24, 26, 28, 30, 32, 36; No. 15, pp. 20, 22, 24, 26 (1951).

Various types of corrosion encountered in pulp and paper mills include oxidation, galvanic attack, pitting, intergranular, stress, crevice, erosion and cavitation. Properties of various corrosion-resistant metals such as nickel, Monel, Inconel, stainless steels are discussed.

(63) J. H. G. Monypenny, "Stainless Iron and Steel," Chapman & Hall, Ltd., London (England), Vol. 1, pp. 80, 351–359, Third Edition (1951).

Deep-drawn stainless steel bowls, drastically cold worked and not annealed, cracked in storage or after brief use. The experiences of Hodge and Miller with stress-corrosion cracking are cited and discussed. Thermowells containing wet ethyl chloride suffered rapid failure. Stress-corrosion cracking has also occurred in 18-8 stainless tubes which have been used in the superheaters of boilers producing highly superheated steam. The tubes reached a temperature of 1050 to 1100 F. Failures were located close to welds with nonaustenitic steel tubes (such as 5 chromium-0.5 molybdenum steel), and were intergranular. Experience with 18-8 superheater tubes in Britain (Davy, C. H., private communication) included failures some of which were intergranular and some transgranular. The former are believed to have occurred mechanically during welding and the latter during exposure to steam.

(64) H. W. Schmidt, P. J. Gegner, G. Heinemann, C. F. Pogacar, and E. H. Wyche, "Stress-Corrosion Cracking in Alkaline Solutions," *Corrosion*, Nat. Assn. Corrosion Engrs., Vol. 7, No. 9, p. 295t (1951).

A discussion is presented of the results of an industry survey on the failure of materials in alkaline solutions. Most of the data have to do with sodium hydroxide. The relationship of temperature and concentration to the cause of failure is expressed only in an approximate manner. Corrective measures that have been employed to eliminate failure are discussed. Data on types 304, 316, 317 and 347 stainless steel are included.

(65) H. Thielsch, "Physical and Welding Metallurgy of Chromium Stainless Steels," *Welding Journal*, Am. Welding Soc., Vol. 30 (Supplement), Vol. 16, pp. 209s–250s (especially pp. 225s to 227s) (1951).

The martensitic and ferritic stainless steels are considerably less susceptible to stress corrosion than the austenitic chromium-nickel stainless steels. Steam has been found to be responsible for stress-corrosion cracking of martensitic stainless steels. Stress corrosion may occur under any condition that favors the discharge of hydrogen ions on the surface.

(66) J. E. Truman, "Tensile Failure of Carbon and Stainless Steel Wires in the Presence of Water and Hydrogen Sulphide," *Metallurgia*, Vol. 43, No. 255, pp. 8–10 (1951); Discussion, p. 248.

Premature failure of both ordinary and corrosion-resisting steels in conditions of service involving the presence of hydrogen sulfide was investigated, and tests carried out on a number of steels. Types of wires used were carbon steel, 13 chromium steel, 18 chromium-8 nickel steel, 18 chromium-8 nickel-1 titanium, and 18 chromium-8 nickel-2 molybdenum. It was shown that the combination of tap water and hydrogen sulfide at room temperature produced a considerable reduction in the life of steel specimens stressed to 40 per cent of their maximum stress, although a chromium-nickel-molybdenum stainless steel showed no visible attack up to 10,800 hr. The investigation is described and tables are given.

(67) H. H. Uhlig, and J. R. Cobb, Jr., "Titanium Resists Stress Corrosion," *Metal Progress*, Vol. 59, No. 6, p. 816 (1951).

Tests were made to determine if titanium is susceptible to stress-corrosion cracking in boiling saturated magnesium chloride and 10 per cent sodium hydroxide. Procedure is outlined. In the sodium hydroxide tests, the container was fabricated from nickel sheet. Two specimens of 18-8 type 304 were set up identically for comparison. In magnesium chloride, within 4 hr the 18-8 specimens cracked at the region of maximum bending. The titanium specimens were still not cracked when the test was discontinued after 62 days and visible corrosion was slight. In 10 per cent sodium hydroxide, at the end of 28 days, neither the titanium nor 18-8 cracked. The titanium was corroded slightly, weight loss being computed at 1.5 mg per sq dm per day and the surface was slightly tarnished. The 18-8 turned black and corroded on the order of 15 mg per sq dm per day.

(68) C. A. Zapffe and M. E. Haslem, "Surface-Active Agents and Pickling Equipment," *Wire and Wire Products*, Vol. 26, pp. 127–133 (1951).

Type 440-C stainless steel is prone to hydrogen embrittlement when pickled in uninhibited acid. The addition of anionic, cationic, or nonionic surface-active agents to the pickling bath had no effect in reducing the embrittlement. The addition of the surface-active agents to a pickling inhibitor known to aggravate embrittlement again had no effect. When the surface-active agents were added to the sole pickling inhibitor known to minimize embrittlement, there was slight, but erractic, improvement. The addition of a foaming compound to an unhibited bath was found to aggravate embrittlement.

(69) C. A. Zapffe and F. E. Landgraf, "Embrittling Effect of Steam on Stainless at Elevated Temperatures," *Steel*, Vol. 128, No. 18, April 30, 1951, pp. 54, 81.

C. A. Zapffe and R. L. Phebus, "Embrittlement of Stainless Steel by Steam in Heat Treating Atmospheres," *Transactions*, Am. Soc. for Metals, Vol. 48, pp. 811–822 (1951).

Tests showing the embrittling effect of steam on stainless steels AISI 410, 414 (containing 1.68 per cent nickel), 430 and 440-C are described. As a result of the observations made, it can be concluded that: steam is a powerful hydrogenizer of steel when contacting the metal at elevated temperatures; bendability values, obtained by a specially devised test, express the damage caused by the hydrogen with good sensitivity; all of class I stainless steels and certain of class II steels such as type 430 are susceptible to embrittlement by the steam-metal reaction; type 410 or 403, designed for steam turbine service, will bend 180 deg when quenched from a dry furnace atmosphere but will fracture at angles as low as 15 and 20 deg if exposed to steam during its hardening heat treatment. This powerful effect of steam is recognizable even within an exposure time of 1 min. Graphs show bendability and recovery of several of the steels.

1952

(70) C. N. Bowers, W. J. McGuire, and A. E. Wiehe, "Stress Corrosion Cracking of Steel Under Sulfide Conditions," *Corrosion*, Vol. 8, pp. 333–341 (1952).

Rapid failures of tubing in a sour condensate well lead to an extensive laboratory and field investigation to determine the cause and remedy for these failures. Apparently, failures occur because of stress-corrosion cracking. Embrittlement resulting from exposure to moist hydrogen sulfide is not considered a primary cause of failures, but it may have been an important contributing factor. The exact mechanism of failure has not yet been definitely established. The failure process can be prevented or appreciably retarded by suitable heat-treatment and/or change in steel composition. Susceptibility to failure of most steels is increased by plastic deformation. In most instances failures were more rapid in field tests, which indicated that the field operating conditions involving pressure, flow, and formation water were more severe than the laboratory test conditions selected. In both tests there was little if any advantage for alloy steels over plain carbon steels. It was apparent, however, that for most steels, limitations on the maximum permissible mechanical properties are just as important and necessary as minimum limits. It is definite that stainless type 410 is a susceptible steel.

(71) J. P. Fraser and R. S. Treseder, "Cracking of High-Strength Steels in Hydrogen Sulfide Solutions," *Corrosion*, Nat. Assn. Corrosion Engrs., Vol. 8, pp. 342–350 (1952) Discussion, p. 357.

Laboratory data are presented relating to the spontaneous cracking and embrittlement of steel alloys under environmental and stress conditions pertinent to sour gas condensate wells. It has been shown that cracking can occur in simple aqueous hydrogen sulfide solutions and is an effect related to stress-corrosion cracking. A mechanism involving stress-corrosion cracking and hydrogen embrittlement is proposed to explain the cracking phenomenon. Important factors studied included composition and heat-treatment of alloy, type and magnitude of stress, composition of corrosive solution (for example, acidity, salt content), composition and pressure of gas environment, temperature and time of exposure. Of these, the first three were found to be the most important. Remedial measures discussed include use of resistant alloys, heat-treatment of susceptible alloys, organic and metallic coatings and inhibition. A simple laboratory procedure is presented for making a preliminary evaluation of the cracking susceptibility of a given alloy. Cracking tendencies in several solutions containing hydrogen sulfide were determined for 12 per cent chromium steel both wrought and cast, for types 302, 316, 410, 430, and 17-4 PH and 17-7 PH stainless steel.

(72) E. Herzog, "Cracking of Ferrous Materials as a Result of Combined Corrosion and Mechanical Stresses," *Metaux*, Vol. 27, pp. 329–357 (1952).

Rupture of materials through the combined effects of corrosion and mechanical stress (static), or through combined effects of corrosion and dynamic stress is discussed. Examination was made of effects produced by corrosion alone, by stress alone, and by the combined effects of stress and corrosion. The nature and mechanism of the various forms of attack, and intercrystalline failure through corrosion-fatigue, are discussed. Testing methods and equipment are surveyed and evaluated. Sections include effects of heat treatment, cooling rate above and below transformation point, hot-rolling, and decarburization. Original work by Herzog and others includes reference to nickel-chromium-molybdenum steels which showed transcrystalline cracking in dilute hydrocyanic acid and to effects of heat treatment on corrosion-resistance of steel containing 0.25 carbon-17 chromium-1.5 nickel. An extensive section on stress-corrosion cracking of austenitic steels is given. Effects of plastic deformation on the behavior of 18-8 steel, notes on results of variation in carbon, chromium, and nickel contents of austenitic steels, data on susceptibility to cracking and corrosion-cracking in type 18-8 as a function of nickel content, degree of cold-work and heat treatment and experiments on corrosion-fatigue of carbon and nickel steels (apparently in aqueous and saline media) are described.

(73) M. E. Holmberg, "Corrosion Problems," *Corrosion*, Nat. Assn. Corrosion Engrs., Vol. 8, No. 3 (1952); Discussion, p. 10.

In this section the following question was raised and answered (abstracted) as follows:

No. 49: Can anyone cite cases of stress-corrosion cracking of stainless steel used for heat exchanger service wherein hot brackish water is known to be the medium causing the cracking?

Many of the refineries and chemical companies along the Gulf Coast report experiences with stress-corrosion cracking in heat exchanger tubes wherein hot brackish water was the cause of stress-corrosion cracking. Even where the water has been treated to reduce the chlorine content, cracking has continued to be a problem.

(74) B. Karnisky, E. Kinelski, and E. Gruca, "Corrosion of Structural Spot Welds," *Welding Journal*, Vol. 31, No. 10, pp. 903–916 (1952).

A procedure was evolved in which various types of spot-welded specimens, 18-8 and a low alloy steel, either stressed or unstressed, were subjected to industrial atmospheric exposure. Results of the test indicate that spot welds may start to fail by corrosion cracking in as little as one year's time unless proper weld sealers are used in the joint.

(75) R. F. Koenig and S. R. Vandenberg, "Liquid Sodium-A Noncorrosive Coolant," *Metal Progress*, Vol. 61, No. 3, pp. 71–75 (1952).

The five known types of attack in liquid metals with illustrations of iron, stainless steel and nickel are given. Solubility studies using sodium for corrosion testing were conducted. The static corrosion test which uses a stainless steel vessel is discussed. Stainless steel types 302, 304, 316, 321, 347 did not change in weight, were unattacked visually and metallographically after a year in pure sodium at 500 C. Type 347 stainless steel was not attacked by clean sodium at 932 F. Four types of dynamic tests, in operating heat transfer systems, are discussed. Stainless steel types 304 ELC, 304, 310, 316, and 347; nickel; 80 nickel-14 chromium-6 iron; and 67 nickel-30 copper were tested with no indication of susceptibility to stress corrosion in sodium at 932 F. No shortening of the fatigue life of type 347 stainless was observed in any of the tests in sodium. The stress-rupture test in sodium indicated that immersion of types 304 and 307 stainless steels in sodium has no effect on their stress-rupture life. A tensile test on wires before and after a standard static corrosion test showed that type 347 stainless, 15 mils in diameter, was as strong both at room temperature and 1000 F after immersion for 5 months in sodium at 932 F as it was after being similarly heated in a sealed can filled with helium. Advantages in a heat transfer system are discussed. Illustrations.

(76) C. J. Lancaster, "Report on Performance of Materials Tested in Water at High Temperature," *U.S. Naval EES Report*, No. 4A(16)966870, March 7, 1952, 10 pp. (Issued as PB 111,962).

Results of two consecutive 30-day dynamic corrosion tests are reported for twelve materials, including stainless steel types 304, 310, 316, 347, Armco 17-14 PH, 17-7 PH, and 17-4 PH. The samples were subjected to a static bending stress while being rotated at a peripheral velocity of 11 ft per sec in oxygenated water at 500 F. The appearances and weight losses were determined after each 30-day run. Corrosion rates for specimens are given.

(77) H. L. Logan, "Film-Rupture Mechanism of Stress-Corrosion," *Journal of Research*, Nat. Bureau Standards, Vol. 48, Feb. 1952, pp. 99–105 (RP 2291).

Atmospherically formed protective films were removed by abrasion in an argon atmosphere from surfaces of an aluminum

alloy, two brasses, a magnesium alloy, low-carbon steel, and type 302 stainless steel. The resulting surfaces were 0.12 to 0.76 volt more negative with respect to a calomel electrode than surfaces prepared and mesured under normal atmospheric conditions. Appreciable changes in electrochemical solution potentials of notched specimens, stressed in tension, occurred at or just above stresses at which the true stress-true strain curves deviated from the modulus lines. These changes in potential were caused by rupturing of the protective films at the roots of the notches and were of the order of 0.16 to 0.70 volt at failure, depending on the material. Stress corrosion is postulated to occur in corrosive media, at stresses sufficient to rupture the protective film, by electrolytic action between the filmed (cathodic) and film-free (anodic) areas.

The process proceeds continuously or discontinuously to failure, depending on whether or not the subsequent adjustment to stresses permits reforming of the protective film.

(78) F. A. Prange, "Hydrogen Embrittlement Tests on Various Steels," *Corrosion*, Nat. Assn. Corrosion Engrs., Vol. 8, p. 355t (1952).

Cathodic embrittlement tests were made on a number of alloys having good properties for use in deep corrosive wells. The tests suggest that the maximum hardness for use in embrittling environments should be Rockwell C 20. 12 per cent chromium steel was included.

(79) R. S. Treseder, "Field Experience with Cracking of High Strength Steels in Sour Gas and Oil Wells," *Corrosion*, Nat. Assn. Corrosion Engrs., Vol. 8, pp. 351–354 (1952).

This is a report by Committee TP-1G on the accumulated field experience of several companies with corrosion cracking of oil well tubular goods and wellhead fittings in sour gas and oil wells. This cracking effect has been associated principally with use of high-strength steels in sour gas-condensate wells. Although relatively few failures have been experienced, the problem is a serious one in view of the high pressures involved and the rapid, unpredictable nature of the corrosive attack. Descriptions of failed tubing, casing, and wellhead fittings are given together with data obtained from stressed specimens of various alloys placed in flowlines of wells in several fields. These data show that sulfide corrosion cracking is associated with alloys of high strength, that is, high hardness, and that the effects may vary among individual wells owing to differing producing conditions and fluid compositions. Possible remedial measures are discussed. With small equipment item the problem of sulfide corrosion cracking has been met by replacing with type 316 stainless or K-Monel.

(80) L. W. Vollmer, "Hydrogen Sulphide Corrosion Cracking of Steel," *Corrosion*, Nat. Assn. Corrosion Engrs., Vol. 8, No. 10, pp. 326–332 (1952).

Sudden blow-out of tubing after only 6 days of production tests of the 12,000-ft Walter Marr Well No. 1, Pincher Creek Field, Canada caused an investigation of causes for failure. Examination of the removed 9 per cent nickel steel tubing showed no obvious defects and calculations showed failures not due to excessive triaxial loading. Investigators, after discarding embrittlement as a cause, initiated tests to determine if stress-corrosion cracking was the cause, because well fluids and gases included 10 per cent hydrogen sulfide and 6.3 per cent carbon dioxide by volume. Specimens of 9 per cent nickel steel tubing were submerged in tap water containing hydrogen sulfide and carbon dioxide in a cell at 5000 psi and 190 F. All specimens failed in 6 days. Numerous other tests of the tubing and other steels at varying loadings were conducted, including prestressed and reheat treated but not prestressed samples. Under laboratory test conditions failure was induced in a 5 per cent nickel-1 per cent chromium steel and types 322 and 410 stainless steels. It is definite that type 410 stainless steel is a susceptible steel. These tests developed the following tentative conclusions: (1) Tubing failures at the Marr well resulted from stress-corrosion cracking. (2) Susceptibility to failure in hydrogen sulfide environments is not limited to 9 per cent nickel steel. Steels treated to produce Rockwell hardness C 24 to 26 may be rendered susceptible. (3) Plastic deformation greatly increases susceptibility to failure, but is not essential if protective corrosion products films are removed. (4) Embrittlement is not a primary cause of failure but may be contributory. (5) Susceptibility may be reduced by composition changes.

1953

(81) H. R. Copson, "The Influence of Corrosion on the Cracking of Pressure Vessels," *Corrosion*, Nat. Assn. Corrosion Engrs., Vol. 10, pp. 124–139 (1954); *Welding Journal*, Vol. 32 Supplement, Vol. 18, pp. 75s–91s (1953).

Serious damage occurring when stress and corrosion combine may take the form of stress-corrosion cracking. Such effects of corrosion on pressure vessels may be minimized by design, by reduction of internal or applied stresses, and by the choice of materials suitably resistant to their expected service environment. Control of the environment itself, by dilution or lowering its temperature, is sometimes practical. Inhibitors are effective in certain instances. Paint, or other protective coatings, and cathodic protection is sometimes employed. Stress-corrosion cracking of iron, stainless steel, copper, aluminum, magnesium and nickel alloys is discussed. Corrosion fatigue data are given for nickel-steel, Monel, nickel, cupro-nickel and stainless steel.

(82) H. R. Copson, "The Role of Corrosion in the Cracking of Metals," *Corrosion*, Nat. Assn. Corrosion Engrs., Vol. 9, No. 12, pp. 4–5 (1953).

A review of present knowledge of the cracking of metals. Under certain conditions, corrosion and stress may cause rapid localized failure in the form of cracking. Caustic embrittlement of boiler steel, season cracking of brass in moist ammoniacal atmosphere, failure of nickel alloys in fluosilicic acid, and the cracking of stainless steels in hot acid chlorides, are discussed.

(83) A. E. Durkin, "Corrosion Cracking of Martensitic Stainless Steel," *Metal Progress*, Vol. 64, No. 1, pp. 72–75 (1953).

Cracking of 12 per cent chromium stainless steel is apparently the result of hydrogen embrittlement and not of stress corrosion as such. The embrittlement is the result of hydrogen released during surface corrosion diffusing into deformed metal structures. If the cracking failures were the result of stress, ductility could not be recovered by the mild and simple treatment of immersion in hot water. The ductility of embrittled steel can be restored by heating at temperatures from 212 F (boiling water) up to 500 F. This treatment will prevent cracking but will not eliminate susceptibility of the steel to future embrittlement.

(84) C. Edeleanu, "Transgranular Stress Corrosion in Chromium-Nickel Stainless Steels," *Journal*, Iron and Steel Inst., Vol. 173, pp. 140–146 (1953).

Tests, made on standard grades of austenitic stainless steels in a magnesium chloride solution, are described. Those grades in which the austenite does not readily transform on straining were found to be less susceptible to cracking. Experimental steels confirmed that such failure can be largely avoided by either increasing the alloy content of the normal 18-8 steels to make the austenite more stable, or by decreasing the alloy content to produce a partly martensitic steel in which the corrosion will be less localized and less likely to cause cracking. Transgranular stress corrosion was obtained in many chloride solutions, including some that were relatively dilute, and there is evidence that oxidizing agents can accelerate cracking. Metallographic evidence indicates that a martensitic phase is produced on straining austenitic steels that is corroded preferentially. The analysis of the steels used in the tests and the test results obtained are tabulated.

(85) R. B. Johnson, Jr., "Jet Engine Metallurgy," *Journal*, Soc. Automotive Engrs., Vol. 61, No. 12, pp. 28–29 (1953).

To study the effect of residual stresses in gas turbine compressor blades, strips of 12 per cent chromium stainless steel were bent to various degrees, then subjected to a corroding medium which was 1 to 1 hydrochloric acid and 1 per cent selenium dioxide. The experimenters concluded that stress level has to be greater than 50,000 psi to produce cracking. Above this stress level, the higher the stress, the shorter the time for failure. Other tests showed that blade hardness influences susceptibility to stress corrosion. To insure against a dangerous level of residual stress in compressor blades, a stress anneal was introduced which reduced the level of stress to a point where the accelerated stress-corrosion test did not produce cracks and eliminated service failures of a stress-corrosion nature.

(86) R. F. Koenig, "New Tests Prove Materials for Nuclear Power Plants," *Iron Age*, Vol. 172, No. 8, pp. 129–133 (1953).

Results of static corrosion tests of most common materials including iron, steel,

stainless steels, cast iron, copper-base alloys, nickel and nickel alloys, and others, in a number of liquid metals, such as sodium, sodium-potassium (NaK), lithium, magnesium and others are listed. After a material shows good resistance to attack in static tests, dynamic tests and the effect of stress are investigated. If the stress-rupture life in sodium is equal to that in air, and there is no metallographic indication of intergranular attack, the material is considered fully resistant to stress corrosion.

1954

(87) W. L. Badger, "Stress Corrosion of 12 per cent Chromium Stainless Steel," *Transactions*, Soc. Automotive Engrs., Vol. 62, pp. 307–310 (1954).

An investigation of stress-corrosion cracking, a combination of stress and corrosive action, in compressor rotor blades of type 403 stainless steel is reported. A laboratory method devised for producing similar failures uses a corroding solution of 1:1 hydrochloric acid and 1 per cent selenium dioxide. Resultant data showed that a minimum tensile stress of about 50,000 psi is required to cause cracking. These data fell in a pattern similar to fatigue or endurance curves. Stress relieving the compressor blades at 950 F eliminated stress-corrosion cracking. Similar testing of 12 per cent chromium-molybdenum-vanadium, 12 per cent chromium-tungsten-nickel, and 12 per cent chromium-molybdenum-tungsten-vanadium alloys indicated that these alloys are more resistant to stress-corrosion cracking than type 403 stainless steel.

(88) A. E. Durkin, "How to Control Hydrogen Embrittlement in 12 per cent Chrome Steels," *Iron Age*, Vol. 174, No. 24, pp. 154–156 (1954).

Problems investigated included (1) the effect of various media in producing hydrogen embrittlement, (2) the effect of different factory heat treatments on the susceptibility of 12 per cent chromium steel (with 0.5 per cent nickel) to hydrogen, (3) the effect of hydrogen on the tensile strength, elongation, and endurance limit of the steel, and (4) the effect of acid and caustic solutions on specific hardness.

Results of tests indicated that the higher the hardness, the more susceptible a material becomes to hydrogen embrittlement. Materials tempered in the 1000 F temperature range show less susceptibility to hydrogen embrittlement than those tempered in a lower temperature range. Organic coatings are used to prevent hydrogen embrittlement by preventing corrosion which results in the formation of hydrogen on the surface of the metal, and subsequently diffuses into the surface of the metal. Acid solutions are more severe than caustic solutions and attack the metal, causing stress-raisers.

(89) M. G. Fontana, "Corrosion," *Industrial and Engineering Chemistry*, Vol. 46, No. 3, March 1954, pp. 99A–100A, 102A.

Metals or alloys (including copper alloys, Inconel, Monel, nickel, steels, stainless steels, and titanium) and environments in which stress corrosion may occur are listed. A number of theories proposed concerning the mechanisms of stress corrosion are discussed. A film titled "A Study of Stress Corrosion" is available from the author's laboratory.

(90) C. Harris, "Corrosion Control in Coil Spring Manufacture," *Corrosion Technology*, Vol. 1, pp. 376–379 (1954).

The problem of corrosion and its influence on spring performance are discussed. Stress corrosion, problems of industrial atmospheres, and protective coatings (including oil, paint and electrodeposition) are covered. Coil springs of steel, stainless steel and nickel, Monel, Inconel and Nimonic alloys are considered. Three metals, namely nickel, cadmium and zinc are used in electrodeposition on springs.

(91) T. P. Hoar and J. G. Hines, "The Corrosion Potential of Stainless Steels During Stress Corrosion," *Journal*, Iron and Steel Inst., Vol. 177, Part 2, p. 248 (1954).

The electrode potentials of several stainless steels under stress-corrosion conditions were measured. Wire specimens in longitudinal tension were exposed to boiling aqueous magnesium chloride solution. Typical potential-time curves for an 18 chromium-10 nickel-3 molybdenum-1 titanium steel are shown. An unstressed specimen gave results generally similar to those given by tin and iron in dilute salt solutions; curves are explained by similar stages in the development of corrosion. Results show that the major part of the life of a moderately stressed specimen under the present, and probably other, conditions of stress corrosion is the development of breakdown conditions in the surface film. In more highly stressed specimens, potential measurements show that the increased stress reduces the time needed for the development of film-breakdown conditions but has little or no influence on the rate of the cracking process once it has started. On specimens exposed to low applied stress, the cracking process does not begin until a long time after film-breakdown conditions have been established.

(92) R. A. Lincoln, "Stress Corrosion in Stainless Steel," *Yearbook*, Am. Iron and Steel Inst., pp. 172–180 (1954); Discussion p. 180.

In stainless steel, the term stress corrosion is often used in a restricted sense and refers to localized transcrystalline cracking found to occur in corrosive conditions that produce relatively mild general corrosion or no corrosion at all in the absence of stress. In contrast to the erratic behavior of the hardenable straight chromium steels, the nonhardening material such as type 430, shows relative immunity to stress corrosion. Unpublished results of tests indicate the possibility that stress-corrosion cracking in 18-8 type may be fundamentally electrochemical in nature.

(93) T. P. May, "Some Aspects of Stress-Corrosion Cracking," *Yearbook*, Am. Iron and Steel Inst., pp. 206–213 (1954); Discussion, p. 213.

Stress corrosion and cracking are defined and examples cited of both nonferrous and ferrous metals in specific environments. Austenitic chromium nickel stainless steel may crack intergranularly if it has been through heat treatments that render it susceptible to intergranular corrosion, or crack transgranular if in the fully annealed condition. Both types of cracks may develop separately in the same material. Chromium steels crack as turbine blades and in sodium chloride. The most acceptable generalized theory to cover all types is that of Mears, Brown, and Dix. They extended the life of 18-8 stainless steel in sodium chloride-hydrogen peroxide solutions by galvanic coupling with more active metals such as zinc, aluminum, and copper. Martensitic chromium steels appear to crack with embrittled by discharged hydrogen.

Considerations of possible mechanisms of stress-corrosion cracking suggest a role played by hydrogen in addition to the electrochemical action that probably occurs in all cases of true stress-corrosion cracking. The possibilities in the hydrogen diffusion seem to justify further research on hydrogen absorption and diffusion by steels with the structures of interest here.

The location of cathodes in the stress-corrosion cracking of magnesium alloys suggests that similar possibilities be explored in the case of ferrous alloys.

The predominant role of chlorides in the environments that may lead to stress-corrosion cracking would dictate intensive fundamental studies on the peculiar role of the chloride ion. A similarly important position is held by this same ion in problems of pitting and crevice-corrosion of the stainless steels. This additional feature, coupled with the economic importance of applications involving contact with chloride solutions, renders a study of chloride ion and its relation to the corrosion of stainless steels a triply important matter.

(94) J. P. Moore, "Maintaining the Corrosion Resistance of Welded Stainless Steel," *Corrosion Technology*, Vol. 1, No. 4, p. 92 (1954).

After-weld corrosion of stainless steels is associated mainly with metallurgical changes in the material brought about by the process of welding. This is illustrated in the case of the austenitic steels by intergranular disintegration or "weld decay" and the "knife line" attack. The process of welding brings about phase formation, and a lowering of the corrosion resistance locally within the material. The process itself with its high heat input, associated with the unusual properties of the steel, results in the formation of high local stresses which, if not relieved, may lead to stress corrosion in service.

(95) A. H. Roebuck, "Water Corrosion of Structural Materials," *Proceedings*, Fifteenth Annual Water Conference, Engrs. Soc. Western Pennsylvania, pp. 165–177 (1954); Discussion, p. 177.

Results are summarized of tests to determine corrosion resistance of stainless steels and other metals in high-purity, high-temperature water to aid in selecting structural materials for atomic reactor systems. Tests were carried out in high pressure autoclaves and circulating systems using high pressure pumps, all of types 347 or 304. Factors influencing corrosion that were studied include temperature, water purity and chemical additions, dissolved gas concentration (oxygen), velocity, pressure, surface preparation, heat treatment, amount of metal working, galvanic coupling, geometry of test sample, and imposed stress. Crevice corrosion, effect of pH, and chloride stress cracking are considered in the discussion. Data are given for austenitic, ferritic, heat-resisting, martensitic, and precipitation-hardening stainless steels, and nickel, Inconel, Monel, Hastelloy, 70-30 copper-nickel, Stellites, and Duranickel among others. Tables, graphs.

(96) R. S. Treseder, "Sulfide Corrosion Cracking of Oil Production Equipment," Report of Technical Unit Committee 1-G on Sulfide Stress Corrosion Cracking, Publication 54-5, *Corrosion,* Nat. Assn. Corrosion Engrs., Vol. 10, p. 413t (1945).

Field experience with sulfide corrosion cracking of production equipment, particularly tubing and casing made of alloy, nickel and chromium steels, and SAE and AISI stainless steels, in sour gas-condensate and high pressure sour oil wells is summarized along with data from recent field tests. Preventative measures currently in use are described. Casing is protected by packing off the annulus and by carefully selecting the fluids placed in the annulus. Tubing is protected by selecting materials of maximum resistance to cracking, keeping applied stresses to a minimum, and employing such secondary measures as inhibitors and protective coatings. Metallurgical, environmental, and mechanical factors involved in the problem of sulfide corrosion cracking are discussed, and future problems involved in very deep sour wells are considered.

(97) W. L. Williams, "Investigation of Cracking in Stainless Steel Auxiliary Boilers for AM 421 Class Mine Sweepers," U. S. Naval Experimental Station Report EES-040038F (6), 32 pp. (1954); *Corrosion,* Nat. Assn. Corrosion Engrs., Vol. 12, No. 4, p. 124 (1956).

Parts of three low-pressure stainless steel boilers were examined after having been steamed approximately 1000 hr. All of the boilers had developed stress-corrosion cracks. Cracks originated from the water side in crevices near welds.

Observations regarding the susceptibility of stainless steel to stress-corrosion cracking in boiler water environments of practical interest show the most critical zones are those in which water-side crevices exist near welded joints. Steps are being taken along three lines: redesign of joints to eliminate crevices; development of special boiler water treatments; and, the use of nonmagnetic constructional materials other than stainless steel.

(98) R. Bakish and W. Robertson, "Internal Deformation Markings in Single Crystals of Cupro-Gold," *Acta Metallurgica,* Vol. 3, p. 513 (1955).

1955

(99) F. K. Bloom, "Stress Corrosion Cracking of Hardenable Stainless Steels," *Corrosion,* Vol. 11, pp. 351–361 (1955); *See also Ibid.,* Vol. 9, pp. 56–65, 103–105 (1953).

The susceptibility of hardenable stainless steels to stress-corrosion cracking depends on the severity of stress, nature of the media, and on their hardness. Horseshoe tests and direct tension tests were conducted in acetic acid, hydrogen sulfide solutions, 20 per cent salt fog, 6 per cent salt solution, and marine and industrial atmospheres. The effects of tempering, hardness and internal quenching stress were studied and the appearance of stress-corrosion cracks examined. Acid-sulfide solutions and chlorides promoted hydrogen embrittlement. The most resistant materials tested were types 422, 17-4 PH and 17-7 PH stainless steels overaged to Rockwell hardness C30. Types 410, 416 and 431 showed good resistance when tempered at 1100 F. Types 304, 305, and 17-10P cracked only in acid-hydrogen sulfide-sodium chloride media. Martempering is helpful in minimizing internal stresses that are generated during quenching and which promote stress-corrosion cracking.

(100) W. K. Boyd, and R. S. Peoples, "Corrosion in Borated and Deionized Water at Temperatures up to 500 F," U.S. Atomic Energy Comm., BMI-1047, p. 19 (1955).

Fully hardened type 440C and 17-4PH stainless steels were susceptible to stress cracking in 500 F borated water. Overaging 17-4PH alloy at 1050 F eliminated cracking. Type 304 stainless, low-alloy steel 4130 and 17-7PH aged at 1050 F were the more resistant materials tested. Type 410 stainless air cooled from 1800 F and tempered at 600 F was also resistant to cracking, exhibiting failure in only the test in liquid borated water at 500 F under a 2:1, H_2-O_2 atmosphere. Aluminum alloy M-257 was the least corrosion-resistant material examined, disintegrating after a 336 hr exposure in 450 F borated water. Beryllium coupled to 2S aluminum and exposed to deionized water at 300 F under a 2:1, H_2-O_2 atmosphere showed pitting attack in contact area as did 61S aluminum when coupled to type 304 stainless. Aluminum alloy 356 exhibited satisfactory corrosion behavior in boiling deionized water, uncoupled to type 304 stainless. Photos, photomicrographs, tables.

(101) J. A. Collins, "Effect of Design, Fabrication and Installation on the Performance of Stainless Steel Equipment," *Corrosion,* Nat. Assn. Corrosion Engrs., Vol. 11, pp. 11–18 (1955).

Several case histories of failures in austenitic type stainless steel chemical process equipment are presented, the recurrence of which are prevented by improved design, better fabrication or installation. Thermal fatigue, concentration cell corrosion and stress-corrosion cracking failures are considered.

(102) M. G. Fontana, "Materials for Handling Fuming Nitric Acid and Properties with Reference to Its Thermal Stability," *Air Force Technical Report No. 6519,* Part V, Wright Air Development Center, (PB No. 111,950), p. 74 (1955).

Corrosion-fatigue studies were made on RemCru-70 titanium, titanium-150-A, Armco 17-7PH, and 2S aluminum in white and red fuming nitric acid at room temperatures; fatigue lives of titanium and 17-7PH are shortened. Tests on 17-7PH show that it is not subject to stress corrosion. Both 3S and 61ST6 aluminum are subject to concentration cell corrosion in white fuming nitric acid. Polarization data on aluminum and stainless steel are presented. The corrosion rate of stainless steel is reduced to very low value by cathodic protection. Experiments were made using platinum as inert anode and current densities of 1.5 to 10 ma per sq in. Numerous diagrams, graphs, tables.

(103) J. J. Heger, "Stress-Corrosion of Stainless Steels," *Metal Progress,* Vol. 67, pp. 109–116 (1955).

Service experiences and laboratory investigations that permit some generalization about conditions under which stress-corrosion cracking will occur in stainless steels are described. The metal has to be simultaneously subjected to stresses and exposed to a corroding environment. Stress corrosion has not been observed in environments that cause rapid general attack. Like pitting and intergranular corrosion, stress corrosion appears to be associated with a localized breakdown of the protective film. Such film breakdown is accelerated by applied or residual stresses. Cathodic protection of stainless steel against stress corrosion was suggested. Findings are summarized in a table listing the contacting metals such as mild steel, aluminum, chromium steel, copper, cupro-nickel, nickel, and platinum.

(104) J. R. Hunter, "Chloride Stress Corrosion of Stainless Steel," *Proceedings,* Sixteenth Annual Water Conference, Engrs. Soc. Western Pennsylvania, pp. 29–33 (1955). (Original paper not published, discussion only given.)

A discussion was given of corrosion of austenitic stainless steel in boiler water. Comparison of types 347 and 304 as boiler materials is given. Results show that chloride ion and oxygen are contributing factors to cracking of stainless steel. Control of chloride concentration, oxygen concentration, wetting-and-drying, temperature, time and stress as factors involved in stress-cracking of stainless steels are discussed.

(105) P. Lillys and A. E. Nehrenberg, "Effect of Tempering Temperatures on Stress-Corrosion Cracking and Hydrogen Embrittlement of Martensitic Stainless Steels," *Transactions,* Am. Soc. for Metals, Vol. 48, pp. 327–346 (1955); Discussion p. 346.

Cracking by stress corrosion and hydrogen embrittlement in types 410, 420, 422, and 436 stainless steels at 300 to 1200 F was determined with beam-type specimens which were stressed below the elastic limit in a 5 per cent sodium chloride spray or as a cathode in a solution of 0.1 *N* (0.5 per cent sulfuric acid plus 3 mg arsenic per liter). Tempering at 500 F provides minimum susceptibility to cracking by hydrogen embrittlement for high hardness. Maximum susceptibility to stress-corrosion cracking and hydrogen embrittlement results from tempering at 800 to 1000 F. Delta ferrite minimizes stress-corrosion cracking by narrowing the range of tempering temperatures which produce susceptibility and by interfering with crack propagation. (500 F is about the temperature at which cementite begins to form,

900 F is about the temperature at which an incoherent carbide begins to form at the parent austenite grain boundaries).

(106) H. J. Noble and W. H. Sharp, "Steels and Protective Treatments for Use Up to 1000 F," *Journal*, Soc. Automotive Engrs., Vol. 63, No. 11, Nov. 1955, pp. 57–61; *Transactions*, Soc. Automotive Engrs., Vol. 64, pp. 59–75 (1956); Discussion, p. 75.

Factors involved in selecting appropriate steels are considered, emphasizing the role of martensitic chromium steels which combine strength with rust resistance. Prevention and effect of rusting, as well as elevated temperature considerations, are discussed. For temperatures up to about 800 F, AMS 5616 (Greek Ascoloy) is to be preferred over AMS 5613 (type 410). At higher temperatures, PWA 722 steel (17-22A) with suitable protection is superior to available martensitic chromium steels. Stress corrosion of martensitic chromium steels is considered. Protective coatings, such as electroplated nickel, electroless nickel plate, and diffused nickel-cadmium plate are reviewed.

(107) R. N. Parkins, "Stress-Corrosion Cracking of Welded Joints," Paper presented at a meeting of the Institute of Welding (N. E. Tyneside branch), Feb. 3, 1955; *British Welding Journal*, Vol. 2, No. 11, Nov., 1955, p. 495.

Stress-corrosion cracking is usually associated with welded joints due to residual stresses remaining in structure. Development of a critical microstructure in heat affected zones may further promote stress corrosion. Furnace annealing at an appropriate temperature is the most reliable practice of avoiding stress-corrosion failures, but peening and controlled low temperature stress relief are used for components which cannot be annealed. Photomicrographs show intercrystalline cracks in aluminum-10 magnesium alloy and transcrystalline cracks in 18-8. Graph shows relationship between stress and cracking time for 0.09 carbon steel in boiling nitrate solution. 26 references.

(108) D. K. Priest, "Some Important Facts You Should Know about Stress Corrosion," *Chemical and Engineering News*, Vol. 33, p. 1683 (1955).

The author first defines and explains stress corrosion, following which he devotes a few paragraphs to the origin of stress in metals. He then reviews briefly some of the stress-corrosion systems, among them austenitic stainless steel. The following is written about the latter: the stress-corrosion cracking of austenitic stainless steel may be divided into two different forms. The first of these is an intergranular cracking brought about by exposure in a suitable environment of a sample which has been sensitized to intergranular attack by heating in the range of 540 to 760 C. In this temperature range, chromium carbide is precipitated at the grain boundaries, which depletes adjacent areas of chromium leaving them susceptible to intense local attack. The presence of stress in such a situation acts to localize further and accelerate the attack. The second form of stress corrosion is transgranular cracking in hot chloride and caustic solutions. The latter is perhaps the more prevalent type of failure.

(109) F. L. Resen, "Why Did Those Storage Vessels Fail?" *Oil and Gas Journal*, Vol. 54, No. 25, pp. 89–94 (1955).

A detailed metallurgical study at Baytown refinery of Humble Oil & Refining Co., of regenerated catalyst hopper and spent catalyst vessels of fluid catalytic cracking unit. Material used in regenerated catalyst hopper was type 304 and welding was done with type 304 electrodes. The spent catalyst hopper and stripper were of type 347. Data obtained from reduced section tensile, bend, Charpy impact, hardness, and Strauss tests and metallographic examination of plate and weld specimens are given. In the type 304 specimens cracks were invariably located in areas demonstrating severe plastic flow manifested by bulging, wrinkling, corrugating or similar distortion. Metal temperatures of 1500 F or greater result in carburization of inside surface, intergranular oxidation of outside surface, and severe distortion. Strauss tests indicated susceptibility to intergranular corrosion. In the type 347 material, failure was by intergranular cracking in areas of highest stress (due to sulfurous and sulfuric acid formation by hydrolysis of iron and nickel sulfide scale). Tables, photomicrographs.

(110) W. L. Williams, "Investigation of Stress-Corrosion of Austenitic Stainless Steels and Other Materials in High Temperature Water Environments. Summary of Work from January, 1951, to January, 1955," *Report EES-040028K*, U. S. Naval Engineering Experiment Station, March 29, 1955, 88 pp.; *Corrosion*, Vol. 12, p. 96a (1956).

Data are summarized from an investigation of the stress-corrosion behavior of various constructional materials in high-temperature water. Data are also presented on the behavior of austenitic stainless steels, martensitic and ferritic stainless steels, nickel base alloys and a few miscellaneous materials. The principal variables studied included alloy composition, stress level, water composition, liquid versus vapor exposure and stress-corrosion inhibitors. Data was obtained from both laboratory tests and experiments with actual equipment.

(111) C. A. Zapffe, "Human Body Fluids Affect Stainless Steel," *Metal Progress*, Vol. 68, No. 1, July, 1955, pp. 95–98.

Mechanochemical attack is more far reaching than previously supposed. Austenitic stainless steels have failed from stresses not exceeding residual effects of cold working and from corrodents no stronger than human perspiration and other products of physiological processes. A recent court case involved the fracture of a type 316 collision plate, 90 days after insertion, while the patient was in bed.

(112) "The Selection and Application of Stainless Steels in the Chemical Process Industries," *Metal Progress*, Vol. 68, No. 2A, pp. 37–49 (especially pp. 38, 39) (1955).

Chloride solutions provide the most severe environment for stress-corrosion cracking to occur. Other environments are hot water of relatively low chloride content, systems containing aqueous hydrogen sulfide, strong hot caustic solution (possibly containing chloride), and vapor in a deaerating water heater. Stress-corrosion cracking is usually transgranular, and sometimes may be accompanied by pitting. The mechanism of stress-corrosion cracking has not been established at the present time.

(113) "Special Alloy for Pipes Under Stress-Corrosion," *Paper Trade Journal*, Vol. 139. p. 38 (1955).

Type 329 stainless steel tubing and pipe are reported to be suitable for applications requiring resistance to stress-corrosion cracking as well as general resistance to corrosion in chlorides, halogen ions, and certain caustic and acid conditions. Type 329 stainless steel cannot be classified strictly as martensitic, ferritic, or austenitic and is reported to be considerably more resistant to stress-corrosion cracking than the austenitic 18-8 chromium-nickel varieties.

1956

(114) I. D. C. Berwick, "A Case History of Stress Corrosion Cracking of Austenitic Stainless Steel," *Corrosion*, Vol. 12, p. 634t (1956).

The stress-corrosion cracking and pitting of stainless steel strainer plates used in pulp mill digesters is discussed and consideration is given to the part played by internal and external stresses in bringing about the plate failures. The corrosive nature of the environment is also considered. A stress-relieving treatment designed to alleviate cracking is described. It was found that a molybdenum-bearing stainless steel heat treated at 1550 to 1600 F for 30 min and followed by air or furnace cooling showed no tendency to stress corrosion, even in severely corrosive media. With face plates made from type 317 stainless steel, stress corrosion was eliminated and pitting corrosion greatly reduced.

(115) S. Brennert and H. Nathorst, "Stress-Corrosion Cracking of Austenitic Stainless Steels in Low Pressure Steam and Hot Water," *Jernkontorets Annaler*, Vol. 140, No. 11, pp. 839–853 (1956); also *Battelle Technical Review*, Vol. 6, No. 11, p. 236a (1957).

Report of experiments on type 316 stainless steel showing that stress corrosion caused by low-pressure steam and hot water is due to stresses of sufficient magnitude, oxygen, and conditions such that hot, strong chloride solution is formed.

(116) P. Cohen, "Coolant Technology In Pressurized Water Reactors," *Proceedings*, Seventeenth Annual Water Conference, Engrs. Soc. Western Pa., pp. 45–57 (1956).

The pressurized water reactor (PWR) primary system is constructed of austenitic stainless steel piping and stainless or stainless-clad carbon steel vessels. Fuel materials are enclosed in envelopes of a corrosion-resistant material such as Zircaloy. Selection of container materials is limited to austenitic stainless or carbon steels. In low oxygen neutral or alkaline water, stainless is very corrosion-resistant. In neutral water corrosion solids are found

largely in the form of a loosely adherent, finely divided magnetite (containing chromium and nickel oxides) as well as a thin film on metal. Behavior of carbon steel is quite similar to that of stainless steel except that corrosion rates for carbon steel are at least ten times as great as stainless steel and susceptibility to pitting is of extreme importance. In contrast, carbon steels appear to be immune to chloride stress-corrosion cracking, which might occur in heat exchanger tubes on secondary side, whereas stainless steels appear to be very sensitive in this respect, if oxygen is present simultaneously with chloride. Functional requirements and chemical problems in pressurized water reactors are discussed. Graphs, photos.

(117) H. R. Copson, "Laboratory Techniques for the Investigation of Stress-Corrosion Cracking," Stress-Corrosion Cracking and Embrittlement (W. D. Robertson), John Wiley and Sons, Inc., New York, N. Y., pp. 187–200 (1956).

Most problems relating to stress-corrosion cracking originate outside of the laboratory. Diagnosis of the failure is the first problem and, to assist in this, a classification of service failures is presented. The next problem is reproduction of the cracking in the laboratory and this usually involves accelerated test procedures. The meaning and significance of residual stresses, applied loads, the corrosion environment, and the internal structure or condition of the metal is carefully considered. Finally comes a désire to correlate the laboratory tests with service experience to find more resistant materials and to predict behavior in related environments. These aspects of the problem are discussed, and the general principles involved in testing procedures for stress-corrosion cracking are reviewed.

It is mentioned that stainless steel cracks may be either transcrystalline or intercrystalline, depending on the steel and the environment. He cites that cracking of stressed austenitic stainless steels in hydrofluoric acid seems to occur only when corrosion rates are high.

(118) A. W. Dana and W. B. DeLong, "Stress-Corrosion Cracking Test," *Corrosion*, Nat. Assn. Corrosion Engrs., Vol. 12, No. 7, p. 19, (1956) (p. 309t).

The stress corrosion of austenitic stainless steel may be caused by contact with a chloride-bearing insulating material. To investigate this effect apparatus has been devised consisting of a U-bend specimen, an insulating block cut to contact the specimen, and a resistance heater taped to the specimen. The block is immersed in deionized water. The heater provides the test temperature and evaporates water in contact with the specimen, causing concentration of soluble material leached from the block. The apparatus may be used to test specific solutions by substitution of an inert wicking material for the insulation block.

(119) C. P. Dillon, "Use of Stainless Steel in Combatting Corrosion in the Chemical Industry," *Corrosion*, Nat. Assn. Corrosion Engrs., Vol. 13, No. 9, p. 124; and No. 10, p. 138 (1957).

Stress-corrosion cracking has been reported in water, condensate, acetic acid, caustic, coffee, baked beans, and tomato soup, and specific instances of such failures are cited. A stress-relief anneal at 1500 to 1750 F is recommended to avoid stress-corrosion cracking. Unstabilized regular-carbon grades of austenitic stainless steel can be used unless intergranular corrosion is expected. Stress-corrosion cracking can also affect the straight chromium steels, chromium-nickel-manganese stainless alloys (200 series), and duplex alloys. One instance is reported of cracking failure of a cast Alloy Castings Institute, grade CH (25 chromium-12 nickel) pump impeller in magnesium chloride brine, apparently due to operational stresses.

(120) C. Edeleanu, "The Phenomena of Stress-Corrosion Cracking in Austenitic Stainless Steels," Stress Corrosion Cracking and Embrittlement (W. D. Robertson), John Wiley and Sons, Inc., New York, N. Y., pp. 126–139 (1956).

The author's previous work on the preferential corrosion and cracking of stress-induced martensite provides only a partial explanation for transgranular cracking in austenitic stainless steel. The mechanism of electrochemical reactions in chloride solutions is explained. It is concluded that the function of corrosion is to trigger the mechanical action that is primarily responsible for failure.

(121) U. R. Evans, "On the Mechanism of Chemical Cracking," Stress Corrosion Cracking and Embrittlement (W. D. Robertson), John Wiley and Sons, Inc., New York, N. Y., pp. 158–162 (1956).

(122) M. G. Fontana, "Stress Corrosion Cracking in Type 403 Stainless Steel," *Air Force Technical Report No. 56-242*, Wright Air Development Center, (PB No. 121, 414), p. 51 (1956).

Determination of the effect of austenitizing temperature on hardness, impact and microstructure of types 403, 420, and 431 stainless. Optimum combination of these properties occurred with the austenitizing temperature of 1725, 1850, and 1900 F respectively for types 403, 420, and 431. Tempered structures displayed minimums in impact strength, tempering temperature curves at 1000, 900, and 1000 F for 403, 420, and 431 steels respectively. Metallographic studies made of stress-corrosion specimens tested in a 1:0 hydrochloric acid and water solution containing 1 per cent selenium dioxide showed that pitting was initiated at manganese sulfide inclusions and that cracking was associated with the pits. Pitting characteristics were dependent on tempering temperatures and therefore are related to microstructure of alloy. Cracking does not occur in type 403 when it is tempered at 1050 F or higher. This temperature is lowered to 900 F for type 420 and it is less than 700 F for type 431 stressed to 75,000 psi and tested in the above solution. Electron microscopy and diffraction studies made of tempered type 403 indicated several carbides to be present after tempering in the 1000 to 1200 F temperature range. Diffraction patterns vary for specimens tempered in this range. Tables, photos, photomicrographs, graphs. Ten references.

(123) W. Z. Friend, "Corrosion Problems in Nuclear Reactor Power Stations," *Proceedings*, Am. Power Conference, Vol. 18, pp. 613–628 (1956).

Discussion of corrosion of construction materials used in nuclear power plants in which water is used both as primary coolant and for steam generation. Metallic materials used in atomic reactors are classified as fuel element or construction materials. Fuel element materials include solid fuels and fuel-cladding. Cladding materials most frequently used to date are aluminum and zirconium alloys and stainless steel and beryllium cladding. Crevice and stress-corrosion cracking in reactors are discussed. Nuclear radiation under high flux density has a significant effect on mechanical and physical properties of metals and alloys which affect corrosion resistance. Corrosion of stainless steels, nickel, Inconel, Monel, copper-nickel alloys and Hastelloys in high purity water is discussed. Tables, graphs, 18 references.

(124) H. P. George, "Evaluation of Stress-Corrosion Effects," *Proceedings*, Third Sagamore Ordnance Materials Research Conference, Durham, N. C., Dec., 5–7, 1956, p. 459.

Stress corrosion is the cracking of metallic materials which results from the combined effect of tensile stress and corrosive environment. The failures are brittle in nature and occur without warning. The stresses may be either applied in service or residual. Residual stresses are developed by any process which creates a nonuniform change in shape by cold working transformations. Applied stresses are rarely the sole cause of stress corrosion; residual stresses are usually the prime cause or at least a contributory cause of service failures. Metals discussed include stainless steels. Photos, diagrams.

(125) L. Graf, "Stress Corrosion Cracking in Homogeneous Alloys," Stress Corrosion Cracking and Embrittlement (W. D. Robertson), John Wiley and Sons, Inc., New York, N. Y., pp. 48–60 (1956).

(126) J. C. Griess, et al, "H.R.P. Dynamic Solution Corrosion Studies (for) Quarter Ending July 31, 1956," CF-56-7-52; *Nuclear Science Abstracts* (U. S. Atomic Energy Commission), Vol. 11, p. 1383 (Nov. 15, 1957).

A laboratory-scale corrosion study has shown the susceptibility of stainless steel to stress-corrosion cracking in boiling simulated HRT fuel solutions containing chloride ions. One phase of a test program to examine the corrosion-fatigue behavior of type 347 stainless steel bellows in UO_2SO_4 solutions at elevated temperatures has been completed. The results indicate that the life of the bellows is not greatly shortened when a UO_2SO_4 solution is used as the corrodent instead of distilled water.

(127) J. J. Harwood, "The Phenomena and Mechanism of Stress Corrosion Cracking," Stress Corrosion Cracking and Embrittlement (W. D. Robertson), John Wiley and Sons, Inc., New York, N. Y., pp. 1–20 (1956).

(128) R. H. Hay, "A Simple Graphical Method for Checking the Adequacy of Stress-Corrosion Specimen Dimensions Against Stress Concentrations," *Corrosion*, Nat.

Assn. Corrosion Engrs., Vol. 12, p. 171t (1956).

A design problem created by the anomalous failure of thin stress-corrosion sheet specimens at the loading pin holes is described. A simple theory, one that takes stress concentrations due to holes and fillets into account, is developed and reduced to a convenient, easy to use graphical form that is explained by example of its use.

(129) J. G. Hines and T. P. Hoar, "The Stress-Corrosion Cracking of Austenitic Stainless Steels: Part II—Fully Softened, Strain-Hardened and Refrigerated Material," *Journal*, Iron Steel Inst., Vol. 184, pp. 166–172 (1956).

Fully softened 18-8 chromium-nickel steels stressed in tension and exposed to aqueous magnesium chloride (42 weight per cent solution at 154 C gave stress-corrosion cracking qualitatively similar to that previously found (Part I) for the same steels in the 'as-received' (fully softened and slightly cold-worked) condition. However, certain duplex steels that fractured at zero applied stress in the 'as-received' condition did not fracture at applied stresses less than about two thirds of the 0.1 per cent proof stress when fully softened.

Plastic strain or subzero treatment applied to fully-softened plain 18-8 steel reduced the time to fracture at any particular applied stress and increased the density of cracking. The quasimartensite formed by either treatment probably provides especially active surface regions for the initiation of stress-corrosion cracks, but plays little part in crack propagation.

(130) T. P. Hoar and J. G. Hines, "Stress-Corrosion Cracking of Austenitic Stainless Steels in Aqueous Chloride Solutions," Stress-Corrosion Cracking and Embrittlement (W. D. Robertson) John Wiley and Sons, Inc., New York, N. Y., pp. 107–125 (1956).

A review of the authors' recent studies concerning electrode potential and current measurements on 18 chromium-8 nickel steel wires in hot aerated 42 per cent magnesium chloride solution. The cathodic process is identified and its activation energy calculated. The current density at the advancing edge of a crack is estimated. The results of cathodic and anodic polarization are given.

(131) T. P. Hoar and J. G. Hines, "The Stress-Corrosion Cracking of Austenitic Stainless Steels: Part I—Mechanism of the Process in Hot Magnesium Chloride Solutions," *Journal*, Iron and Steel Inst., Vol. 182, pp. 124–143 (1956).

Austenitic stainless steel wires of several usual compositions based on 18 chromium-8 nickel, stressed in tension, have been exposed to 42 per cent aqueous magnesium chloride solution at 135 to 154 C. The apparatus used for the tests provided for measurement of the corrosion potential and for the extension measurement of the exposed specimens during test.

Potential-time curves obtained with unstressed specimens show a rise to a maximum followed by a fall, and are generally similar to those obtained on tin and on mild steel under conditions where oxide-film repair is followed by film breakdown and pitting. Stressed specimens behave similarly in the early stages of exposure, the potential first rising steadily; it then falls relatively rapidly, however, during the last few minutes before fracture of the wire. Extension measurements during tests and the mechanical properties of specimens removed before fracture indicate that crack propagation takes place only during the final rapid potential fall and thus usually occupies only a small part of the total life of a specimen. At high applied stresses, cracking begins before oxide-film repair as indicated by the potential rise is complete. At low stresses cracking does not begin until some time after film breakdown. At high applied stresses the over-all process is very sensitive to temperature; the apparent activation energy for the process of the induction period before cracking being about 40 kg-cal per g molecular weight and that for the process of crack propagation about 10 kg-cal per g molecular weight.

At high applied stresses, the times to fracture of steels of different compositions are similar and not greatly influenced by the stress value. Generally, the influence of variation of composition is indirect and much less marked than that of other factors such as mechanical and surface conditions.

At low stresses the times to fracture are very sensitive to the stress value. Although stress has little influence on the processes occurring during the induction period of corrosion damage preceding crack propagation, the rate of crack propagation is substantially independent of the stress value. More extensive corrosion damage is required before cracks can be initiated by lower stresses.

The results are discussed in terms of corrosion processes similar to those found in known cases of film repair and breakdown; of crack initiation at susceptible points on the bare metal surface; and of crack propagation by the rapid anodic dissolution of highly stressed and strained metal.

Preliminary experiments have shown that the processes occurring during the induction period and crack propagation can be greatly retarded by relatively mild cathodic protection.

(132) M. R. Hyslop, "The Case of Chloride Ions," *Metal Progress*, Vol. 70, No. 5, p. 90–92 (1956).

A type 304 tank used to hold maleic anhydride suffered from stress-corrosion cracking when chlorides leached out from the insulation due to a steam leak and concentrated where water in the leachings evaporated. Breaks in tar coating also admitted rain water contaminated by free chlorine and sulfur chloride in the atmosphere. Recommendations included heat treatment to eliminate residual stresses from fabrication of the tank, painting prior to insulation, and change in tank design. Photomicrograph shows branch cracks typical of stress corrosion.

(133) G. Klingel, "Stress-Corrosion Cracking of Stainless Steel," *Metal Progress*, Vol. 69, April, 1956, pp. 77–78.

Surface stress is often present in hardened stainless steel parts even after stress-relieving treatments. Removal of a thin surface layer after heat-treatment can prevent stress-corrosion failures.

(134) H. L. Logan and R. J. Sherman, "Stress-Corrosion Cracking of Type 304 Austenitic Stainless Steel," *Welding Journal*, Vol. 35 (Supplement), Vol. 21, pp. 389s–395s (1956).

In a study of the mechanism of stress-corrosion cracking, approximately 40 solutions were investigated as possible corrodents to be used in stress-corrosion tests of types 304 and 304L stainless steels. A boiling 3½ per cent sodium chloride-1 per cent commercial ammonium nitrite solution, pH 7.0, produced stress-corrosion cracking in a few hours in the 304 steel stressed to 80 per cent of yield or more, and in the 304L steel stressed to 100 per cent or more of their room temperature yield strengths. Cracking was produced in 0.2-in. gage lengths strained 0.5 per cent or more. There was, however, no correlation between macroscopic strain and tendency to develop stress-corrosion cracks. Pitting was generally produced by solutions having pH's less than 4.0. Studies of the development of cracks, made both by interrupting tests and by photographing specimens *in situ* indicated that stress-corrosion cracks can develop with little, or possibly no, previous pitting. Gas, believed to be hydrogen, was shown escaping from cracks. Corrosion products contain metal ions in approximately the same proportion as the parent metal. Limited data indicate that stress-corrosion cracking is not limited to any particular crystallographic plane or set of planes.

It is postulated that stress-corrosion cracking of type 304 stainless steel results from rupturing of the passive film by the application of stress under conditions favorable to the formation of oxygen concentration cells.

(135) R. B. Niederberger, "Stress-Corrosion Tests of Stainless Steels in High Temperature Waters," Naval Engineering Experiment Station, Report EES-040028M (1956); *Corrosion*, Nat. Assn. Corrosion Engrs., Vol. 13, No. 2, p. 139a (1957).

Stress-corrosion cracking occurred in all specimens exposed to liquid and vapor phases of chloride-bearing boiler water, except type 430 stainless steel. The results confirm the conclusion, that austenitic stainless steels as a class are subject to stress-corrosion cracking in high temperature waters containing chlorides and oxygen. Steels tested included: types 304 and 430, 6 austentitic steels with nickel contents from 10 to 40 per cent, and Carpenter-7 molybdenum.

(136) W. G. Renshaw, "Nature of Stress-Corrosion Cracking of Stainless Steels When Other Types of Corrosion are Present," *Corrosion*, Nat. Assn. Corrosion Engrs., Vol. 12, pp. 477t–478t (1956).

Stress corrosion and intergranular corrosion can occur simultaneously and only a few grains apart. Two cases are cited where molybdenum bearing stainless steels which had failed primarily by each mechanism, but which had suffered combined attack from the other as well. Both types of failure are evident on each photomicrograph.

(137) A. V. Riabchenkov and V. M. Nikiforova, "The Mechanism of Corrosion Cracking

in Austenitic Steels," *Metallovedeniei Obrabotka Metallov* (U.S.S.R.), No. 8, Aug., 1956, p. 2. (In Russian.)

Electrochemical factors are very important in initiating and developing corrosion cracking. It is claimed that a potential difference is the basic cause of failure.

(138) K. S. Sarma, "Stainless Steel for Corrosion Resistant Service," *Product Engineering*, Vol. 27, No. 8, pp. 370–371 (1956).

After exploring the relevant properties of 18-8, the article describes their effect on fabrication and design of welded equipment for corrosive service. Gas welding is used with very thin sheets while arc welding is most generally used. Distortion of parts in or near weld in stainless steel is considered. Exposure of hot zone to atmospheric oxygen reduces corrosion resistance at joint; hence, the need for coated electrodes or inert shielding gas. Design stresses and stress corrosion, electrolytic cell corrosion, chloride corrosion and passivation are considered.

(139) H. Thielsch, "Here Are Some Answers to Stress-Corrosion Cracking of Your Piping," *Paper Trade Journal*, Vol. 140, No. 20, pp. 44–46 (1956).

Stress-corrosion cracking and corrosion fatigue in vessels and piping containing acids or caustic, and in power plants, and steam generating and transmission systems of pulp and paper mills, are considered. Causes of static tensile stresses and cyclic stresses, and the effects of steam and water composition, are discussed. The most important factor contributing to stress-corrosion cracking is the condition of butt welds along the inside of piping. Proper joint design, preparation and welding are reviewed.

(140) D. C. Vreeland, and S. H. Kalin, "Corrosion of Metals by Liquid Fertilizer Solutions," *Corrosion*, Nat. Assn. Corrosion Engrs., Vol. 12, No. 11, p. 569t (1956).

Laboratory corrosion tests conducted on aluminum, carbon steel, 5-chromium steel and types 405, 430, 302, 304L, and 316L to determine their suitability as materials for storage, transport and applicator tanks for "nitrogen" and "complete-mix" liquid fertilizers. Tests conducted were partial immersion of small specimens in each fertilizer solution, and simufated service tests in which small tanks labricated of each material were partially filled with each of test solutions. Tank tests were also used as stress-corrosion tests since tanks were not stress-relieved after welding. Weight-loss, thickness, pitting depth and metallographic examinations determined amount and type of corrosion. In the ammonia-ammonium nitrate solution and ammonium nitrate solution, aluminum and several of the chromium and chromium-nickel stainless steels were resistant. In mixed solutions, only the chromium-nickel stainless steels were not attacked. Tables, graphs.

(141) W. L. Williams and J. F. Eckel, "Stress-Corrosion of Austenitic Stainless Steels in High-Temperature Waters," *Journal*, Am. Soc. Naval Engrs., Vol. 68, No. 1, pp. 93–104 (1956).

The results of an extensive laboratory test program on stress corrosion of austenitic stainless steels in high temperature water and steam are given. A brief description of procedure, conclusions reached, and illustrative data only as needed for clarity, are included. Following a literature review, results of tests of small laboratory specimens, and of small boilers made of welded type 304 stainless steel, are discussed. Numerous tests were conducted in alkaline-phosphate treated waters. Cracking was predominantly transgranular. The use of annealed steels, stress-relief treatments, stabilized grades of stainless steel, low operational stresses, low chloride levels, low oxygen levels, and proper corrosion inhibitors are all important steps toward elimination of stress-corrosion hazards.

1957

(142) G. M. Adamson, J. P. Hammond, T. M. Kegley, and J. K. White, "Metallurgical Examination of HRT Leak Detector Tubing and Flanges," U.S. Atomic Energy Comm., ORNL-CF-57-1-109, p. 25 (1957).

After several failures occurred in the HRT (homogeneous reactor test) leak detector system, several lengths of the 304 stainless tubing were removed for metallurgical examination. Chloride contamination entered the system in a portion of the first lot of tubing used for shield penetration. In the leak detector system, cracks were found that extended entirely through the tube wall. While these cracks were typical chloride stress-corrosion cracks, they formed under very low stress levels. A complete replacing of tubing was necessary. Cracks are found in two out of four high pressure flanges examined. Cracks were not deep but were present in area of highest stress; replacement was required. Photomicrographs.

(143) E. B. Backensto, "Survey Reveals Reformer Corrosion Data," *Petroleum Refiner*, Vol. 36, pp. 201–204 (1957).

A panel report on a 31-company survey shows most frequently encountered difficulties related to catalytic reformer corrosion are: excessive metal loss (above that anticipated); heavy scaling of furnace tubes, exchangers and transfer lines; plugging of catalyst beds; fouling of heater and exchanger tubes; stress-corrosion cracking of austenitic stainless steel; and pitting or condensate-chloride corrosion. Other problems considered are: hot spots in furnace tubes, high-temperature hydrogen attack on carbon steel reactor internals, carburization, dezincification, and fatigue failure due to vibration. Preventive measures include: proper alloying, generally with 18-8 at high temperatures; feed-stock desulfurization, hydrogen sulfide removal in recycle gas; aluminizing; acid cleaning to remove scale; and radial flow reactors or mechanical scale catchers.

(144) E. G. Bohlman and G. M. Adamson, "Stress-Corrosion Cracking Problems in the Homogeneous Reactor Test," *Paper No. 57-NESC-111*, Am. Soc. Mechanical Engrs., p. 21 (1957).

Chloride-induced stress corrosion was encountered in an 18-8 stainless homogeneous reactor test during preliminary testing. Reactor is unique in that it will operate at 250 to 300 C with an aqueous uranyl sulfate solution fuel containing 200 to 500 ppm of dissolved oxygen. Cracking occurred in a secondary system used for detecting leaks in flanged joints of primary systems and in grooves of flanges in primary systems. Tubing used in leak-detection system was found to be contaminated with chloride introduced during manufacture. Tests show that stress-corrosion cracking of types 304 and 347 stainless does not occur in oxygenated uranyl sulfate solutions unless chlorides are present. Composition is given of contaminated solution from Homogeneous Reactor Test (HRT) Leak-Detector system includes nickel and chromium content. Photomicrographs, diagrams, 10 references.

(145) W. K. Boyd and H. A. Pray, "Corrosion of Stainless Steels in Supercritical Water," *Corrosion*, Vol. 13, No. 6, pp. 33–42 (1957); Discussion p. 42.

Behavior of 12 stainless alloys (types 410, 302, 347, 309, and 310, Armco 17-7PH, 17-4PH, Allegheny A-286, Inconel-X, Hastelloy F, Hastelloy X, and AMS 5616), including both hardenable and nonhardenable grades, in degassed supercritical water at 800, 1000, and 1350 F, and a pressure of 5000 psi is described. In general, corrosion at 1350 F was found to be intergranular, while at 1000 F, only Inconel-X exhibited selective penetration along grain boundaries. All alloys suffered some decarburization and carbide precipitation after exposure to 1350 F supercritical water. No significant phase changes were observed at 800 and 1000 F. Armco 17-7PH, Armco 17-4PH, and Hastelloy F alloys were most resistant materials at 1350 and 1000 F. All alloys exhibited excellent resistance to 800 F degassed supercritical water. AISI type 316 was shown to be susceptible to stress-corrosion cracking at 1360 F. Tables and graphs summarize corrosion data. Photomicrographs.

(146) B. W. Bradley and N. R. Dunne, "Corrosion Measurements in a Hydrogen Sulfide-Water Absorption Pilot Plant," *Corrosion*, Vol. 13, No. 4, pp. 30–34 (1957).

Series of corrosion evaluation tests were run concurrently in a pilot plant constructed to evaluate high-pressure water absorption followed by simple low-pressure flashing as a means of sweetening sour natural gas. Carbon steel corrosion rates, although high initially, diminished to tolerable level within the 19-day test. Killed carbon steel, type 304, Inconel, and K-Monel were resistant to sulfide stress-corrosion cracking. Inconel, Monel, and type 304 showed low weight loss. Hydrogen-probes indicated decreasing corrosion rates in absorber and degasifying drums. Water dispersible, amine-type inhibitor reduced carbon steel corrosion rates and indicated protection from stress-corrosion cracking. Among other materials tested in form of coupons were N-80, J-55, 9-nickel steel, SAE 4340, Ni-Resist, Carpenter 20, types 302, 316, and 410, and nickel. Data indicate stress-relieved carbon steel vessels and piping with type 304 or 316 pump casings, impellers and shafts, and K-Monel impeller rings, Bourdon tubes, and relief valve springs. Tables, graphs.

(147) W. F. Brindley, L. R. Scharfstein, and M. A. Golik, "Chloride Stress-Corrosion Testing of Type 347 Stainless Steel Steam

Generator Tubing," U. S. Atomic Energy Commission, WAPD-BT-3, pp. 1–22 (1957), (also *Bettis Technical Review*, Vol. 1, No. 3).

Cracks in the stainless steel tubing varied in depth, averaging from 5 to 10 mils. The majority of cracks observed extended at least half-way around the circumference. The conditions of this test, particularly the considerable quantity of oxygen in the vapor, are extremely severe and are unlikely to occur in practice. However, they do serve to give comparative results on an accelerated basis. It appears that exposure to the vapor for an extended period of time was necessary to cause cracking. Inasmuch as the vapor consisted of rather large amounts of oxygen it may be concluded that steam and oxygen are an important part of the mechanism leading to chloride stress-corrosion cracking. The fact that cracking can occur in a deformed tube in a crevice, with very little likelihood of chloride concentrating in a test of this nature, points to the important influence of the gaseous oxygen. Tables, photomicrographs.

(148) E. G. Brush, "Behavior of Type 347 Stainless Steel in Sodium Hydroxide at Elevated Temperatures," Report *Kapl-M-EGB-22*, U.S. Dept. of Commerce, July 12, 1956; NSA 11,1198, Oct. 15, 1957-S.

Tests have been performed in various NaOH mixtures to investigate expected behavior of type 347 stainless steel in the S2G third fluid sodium-potassium filled system in the event of a water leak. Idealized capsule tests show stress-corrosion cracking to be severe in 100 per cent NaOH and in NaOH solutions containing appreciable amounts of water. Tests of NaOH plus various additives show, however, that if the corrosion rate can be made to exceed 5000 mg per sq dm per month the tendency to crack is reduced. The most promising additive seems to be NaH.

(149) F. E. Clark and A. J. Ristaino, "Investigation of Chemical Inhibitors for Stress-Corrosion Cracking of Stainless Steel," Summary Report for Jan. 1954 to June 1957, EES-010359A (1957), *Nuclear Science Abstracts* (U. S. Atomic Energy Commission), Vol. 12, p. 675 (1958).

(150) H. R. Copson and C. F. Cheng, "Some Case Histories of Stress Corrosion Cracking of Austenitic Stainless Steels Associated With Chlorides," *Corrosion*, Nat. Assn. Corrosion Engrs., Vol. 13, No. 6, p. 397t (1957).

Some 22 case histories of stress corrosion cracking in types 302, 304, 316, 321, and 347 stainless steels are presented. These occurred in water, steam, brines, and miscellaneous solutions. In each case, either the chloride content was high initially, or conditions were such that chlorides could concentrate. Usually the temperature was quite hot. Often the environment was acid and in most cases it seemed likely that air was present. Microexamination always revealed transcrystalline cracks which usually had a characteristic branching growth. In each case it was concluded that internal tensile stresses in combination with concentrated chlorides caused the cracking. Some means of avoiding cracking are pointed out. Following the case histories the results of some laboratory tests are presented which show that resistance to cracking increases with nickel content, and that large additions of nickel bring about a major improvement. Inconel, which is at the high-nickel end of this series of alloys is considered immune to this type of stress-corrosion cracking.

(151) A. W. Dana, "Stress-Corrosion Cracking of Insulated Austenitic Stainless Steel," ASTM BULLETIN, No. 225, Oct., 1957, p. 46 (TP196).

The phenomenon of stress-corrosion cracking which may occur when austenitic stainless steels are exposed to moist thermal insulating materials is believed to result from the action of water-soluble chlorides leached from the insulations. Chemical analyses showed that water-soluble chlorides are present in 85 per cent magnesia, calcium silicate, and glass fiber insulating materials, with little difference in chloride level between them. Simulated service tests indicated that 85 per cent magnesia insulation had the greatest tendency to produce cracking at 100 C. After 200 days of exposure, no statistically significant difference in cracking tendency was present between calcium silicate and glass fiber insulations.

(152) J. Dedieu and L. Pennec, "Analysis of Types of Corrosion Encountered in 18-8 Stainless Steel Tubing: Causes and Prevention," *Corrosion et Anticorrosion*, Vol. 5, pp. 348–358 (1957).

A discussion of corrosion failures of 18-8, 18-8 molybdenum and 18-8 copper-molybdenum tubing, including failure due to intergranular and stress corrosion, fissuring and weld decay. Notes on methods of prevention and control, including prior heat treatment are given.

(153) D. J. DePaul, "Corrosion Engineering Problems in High Purity Water," *Corrosion*, Nat. Assn. Corrosion Engrs., Vol. 13, No. 1, p. 75t (1957); Discussion, p. 79t.

Important corrosion problems are encountered in systems exposed to recirculating high-purity water with respect to particular engineering application of materials. Most of the evaluations and remarks are based on exposure to high-purity water at 500 to 600 F at velocities up to 30 ft per sec. Special attention is given to crevice corrosion of buildup and pitting types, galvanic, intergranular and stress corrosion. Materials considered include 18-8 types and straight chromium stainless steels, nickel-, cobalt-, and copper-base alloys, and hard chromium plate. Graphs show effects of oxygen, clearance and temperature on crevice corrosion. In discussion, J. E. Draley considered aluminum-nickel alloys and plating of aluminum with Kanigen electroless nickel to prevent high purity water attack.

(154) C. Edeleanu, "Avoidance of Stress Corrosion in Austenitic Steel Equipment," *Chemical and Process Engineering*, Vol. 38, No. 5, pp. 181–184 (1957).

Transgranular stress corrosion is a failure which occurs with all normal austenitic stainless steels. Failure is rapid only with concentrated chloride or caustic solutions and only at elevated temperatures. With concentrated solutions, such as 42 per cent magnesium chloride, most 18-8 steels, whether tested as U-bends or as tensile specimens loaded to a known extent, give a very similar life and there is no appreciable difference between stabilized material and plain 18-8 steels. Certain casts of titanium stabilized steel do sometimes give long lives and there is some correlation between delta ferrite content and susceptibility of this steel to cracking. A similar effect was noticed with plain chromium-nickel steels and in certain casts of chromium-nickel-molybdenum steels. An improvement can also be achieved by increasing the nickel content of steels and there are both niobium and titanium stabilized steels available commercially with about 11 to 13 per cent nickel. Higher nickel steels are even less susceptible, but as nickel is increased, various manufacturing and fabrication difficulties are met. Photomicrographs.

(155) C. Edeleanu and P. P. Snowden, "Stress Corrosion of Austenitic Stainless Steel in Steam and Hot-Water Systems," *Journal*, Iron and Steel Institute, Vol. 186, pp. 406–422 (1957).

An investigation is reported on conditions under which stress corrosion and cracking occur in austenitic stainless steels in steam and hot water. The effects of temperature, pressure and contamination with chloride or hydroxide ions are discussed.

(156) G. E. Galonian and H. L. Tymchyn, "Results of Stress Corrosion Cracking Tests of Retort Annealed and Resistance Annealed T-347 Stainless Steel Tubing," *KAPL-MEMO-GEG-10*, U. S. Atomic Energy Commission, 17 pp. (1957).

The results of chloride stress-corrosion cracking tests of resistance-annealed and retort-annealed T-347 stainless steel steam generator tubing are given. These tests were made in a tilted autoclave exposing unstressed tube sections and stressed U-bend tubing to alternate wetting-and-drying with 500 F air-saturated boiler water. Nine resistance-annealing treatments and one retort-annealing treatment were investigated. Based on the number of cracks found and general corrosion resistance, tubing brought to resistance-annealing temperature in $\frac{3}{4}$ to $1\frac{3}{4}$ min appears to be as resistant to cracking as retort-annealed tubes. Retort-annealed tubes are more resistant to general corrosion than resistance-annealed tubes. With the application of stress to resistance-annealed tubing more resistance to cracking is obtained with heating times of $\frac{3}{4}$ to $1\frac{3}{4}$ min than when shorter or longer times are used. Areas in the vicinity of electrical clamps on resistance-annealed tubes are less resistant to corrosion and cracking than other sections of tubing. Tables and graphs.

(157) H. Gerischer, "Stress-Corrosion—Electrochemical Processes," *Werkstoffe und Korrosion*, Vol. 8, p. 349 (1957); *Metals Review*, Vol. 30, p. 52 (1957).

The narrow localization of the corrosion process is caused by the mechanism of plastic deformation. Under plastic deformation the atoms on the lines of the slip planes or on slipping grain boundaries along the surface will be activated and dis-

solved favorably. As a result, protective coatings are formed on the surface of all alloys susceptible to stress corrosion. Cracking of these covers under plastic deformation increases the localization of the corrosion process and causes the phenomenon of tension crack corrosion. Nineteen references.

(158) E. A. Gulbransen, T. P. Copan, and D. Van Rooyen, "Structural Aspects of the Corrosion of Stainless Steel at 500 to 700 C in Gaseous Atmospheres," Paper before Am. Inst. Mining, Metallurgical, and Petroleum Engrs., 2nd World Metallurgical Congress, Chicago (1957), *Chemical and Engineering News*, Vol. 35, pp. 45, 49 (1957).

Crystals which grow as delicate plates from the surface of stainless steel may explain metal failure attributed to stress corrosion. They form on strongly stressed stainless steel specimens which are exposed to corroding atmospheres containing traces of chloride ions. This growth of platelets on the surface could lead to chemical cutting of metal. As platelets grow above the surface, minute crevices might grow downward into the metal surface, leading to concentration of stress at base of crevices. Subjected to very pure oxygen and water vapor, the surface of typical specimen erupts with billions of oxide whiskers; their density is about six billion per square inch. Unexpected changes occur in crystal growth simply by prestressing the stainless steel and adding less than five parts per million of chloride ions to the atmosphere. Instead of long thin filaments, rows of thin, upright, parallel plates grow in definite crystallographic direction. Electron micrographs.

(159) P. H. Harley, "Stress-Corrosion in the Homogeneous Reactor Test (HRT) Mockup," U. S. Atomic Energy Commission, ORNL-CF-57-5-98 (1957). 20 pp.

A summary of failures which occurred in the HRT mockup. All of the failures have occurred in type 347 stainless steel parts except type 321 O-ring and type 304 cap screw. All instances of cracking were found in areas which contained stagnant liquid or low flow. In several cases, crevice corrosion which was caused by low flow and oxygen depletion was also observed. Solids or scale were found in all cases of the crevice type of corrosion. Operational life of the different equipment varied from 24 to 8000 hr before cracks were found. Temperature at location of failures varied from −150 to +305 C. All failures occurred in high pressure system of loop. Photomicrographs.

(160) G. W. Hinkle, "Production and Fabrication of New AISI Types 201 and 202," ASTM BULLETIN, No. 220, Feb. 1957, p. 47 (TP35).

This paper summarizes information on melting practice, hot- and cold-rolling in blooming and strip mills, forging, annealing, pickling, brake- and roll-forming, deep drawing, polishing and welding of AISI types 201 and 202. Table lists effects of lower annealing temperature (1800 to 1950 F) on mechanical properties. Charts show cold rolling practice, oxidation characteristics, and hardness and gage surveys of deep-drawn parts. Stress-corrosion cracking tests in boiling 10 *M* lithium chloride show no difference in cracking of comparative samples of drawn 201, 202, and 302.

(161) T. M. Krebs, "Corrosion of Ferrous-Metal Tubing. How to Prevent Stress-Corrosion Cracking," *Oil and Gas Journal*, Vol. 55, No. 20, p. 207 (1957).

Erosion-corrosion problems result from combination of corrosion plus mechanical sweeping away of corrosion products by a high-velocity stream with associated metal loss. This is common at bends or at inlet ends of heat exchanger or refinery heater tubes. Sulfur compounds in presence of water emulsified with oil result in corrosion with formation of sulfates. For ferrous materials the most familiar occurrence in refinery situations is cracking of austenitic stainless steels in chloride-bearing environments. Sometimes accompanied by chloride pitting, this type of cracking occurs transgranularly and usually with little actual metal loss. Concentration of chlorides in cooling water led to stress-corrosion cracking of a type 347 tube from inside while leaching of magnesium chloride salt from wall refractory during shutdown led to severe cracking of tubing from the outside. In this case stresses were largely of thermal origin but may be from bending, welding, straightening or fluid pressure. Photomicrographs.

(162) O. Lissner, "Stress Corrosion in Austenitic Steel by Nitrates," *ASEA Journal*, Vol. 30, No. 5, p. 85 (1957). (In Swedish.); *Engineers Digest*, Vol. 18, No. 12, pp. 57–571 (1957).

Intergranular cracks developed in an austenitic steel of unspecified composition in service as an end bell in a turbo-generator installation. Samples of the metal subjected to chloride-containing test solutions developed only transgranular cracks, but in a calcium-ammonium nitrate solution rapidly formed intergranular stress-cracks. A manganese-chromium steel (no analysis) also developed intergranular cracks in the nitrate solution. Nitrate deposits were found in connected equipment. Improved materials suggested for this service application are austenitic stainless steels. Two showing "satisfactory results" in both chloride and nitrate solutions are 12 chromium-12 nickel-6 manganese-0.2 carbon steel, and 12 chromium-20 to 24 manganese-0.08 to 0.20 carbon (no information on nitrogen content).

(163) T. Marshall and A. J. Hugill, "Corrosion by Low-Pressure Geothermal Steam," *Corrosion*, Nat. Assn. Corrosion Engrs., Vol. 13, No. 5, p. 59 (1957) (p. 329t); Discussion, p. 67 (p. 337t).

With view to using geothermal steam for electrical power production, the New Zealand Dept. of Scientific and Industrial Research investigated corrosive properties of the steam in contact with turbine and condenser alloys. Low- and high-velocity corrosion tests were conducted in geothermal steam containing hydrogen sulfide and carbon dioxide and steam-water mixtures containing chlorides in addition. Detailed results are given for a range of common engineering alloys including Ni-Resist, high-silicon and gray cast irons, 4.7 nickel steel, various 18-8 steels, 35-10 nickel-chromium stainless, Rex 326 stainless steel, Monel, Inconel, nickel and nickel-plated steel, among others. Stress corrosion, erosion corrosion and hydrogen embrittlement are discussed. Tables.

(164) K. Matthaes, "Stress-Corrosion and the Theory of Tenacity," *Werkstoffe & Korrosion*, Vol. 8, p. 261 (1957); *Chemical Abstracts*, Vol. 52, p. 17054 (1958).

Danger of cracking by stress corrosion depends both on the mechanical and chemical stress of the material. Conditions for occurrence are (1) the presence of two different kind of atoms in the same lattice, and (2) the presence of elastic or hyperelastic stresses. A corrosive agent must act, attacking the mixed crystal; a potential gradient must exist between the components of the material; and there must be solvent action by the corrosive agent. As foreign atoms influence the elastic limit and flow properties, each stress causes a change in linkage and in the electrochemical potential.

(165) A. B. McIntosh, "Corrosion Problems in the Production of Nuclear Power," *Chemistry and Industry*, p. 687 (1957); Discussion, p. 166.

Maintenance is possible in chemical plants for extraction of uranium, but not in plants where plutonium is extracted. Development of chromium-nickel austenitic steels for constructional materials was considered. Cooperative effort resulted in adoption of 18 chromium-13 nickel stabilized by 1 per cent niobium which was not lost during welding. 18-13-1 niobium corrodes at less than half the rate of 18-8-titanium in 70 per cent (by weight) nitric acid at the boiling point such as used in the plutonium separation process. Effects of various influences on corrosion of stainless steels and welds, inhibition of accelerated corrosion by nitrogen dioxide and mechanism of corrosion of stainless steel in boiling nitric acid were discussed. Further problems considered included corrosion of magnesium alloy cans (used to store fuel elements under water during cooling), corrosion of stainless and mild steels in water at high temperature, zirconium, aluminum and their alloys. In discussion, T. P. Hoar questioned reference to stress-corrosion cracking of stainless steel in steam containing no trace of chloride.

(166) W. C. Rion, Jr., "Stress-Corrosion Cracking of Austenitic Stainless Steels in Chemical Plant Equipment," *Industrial and Engineering Chemistry*, Vol. 49, No. 3, pp. 73A, 74A, 76A, 78A (1957).

Some case histories of condensers and heat exchangers, cooling coils, in contact with wet thermal insulation are given. In all failures that were investigated, aqueous media containing chlorides were involved. It was impossible to establish the minimum chloride content at which cracking would occur because there was evidence in all cases that concentration of chlorides had taken place. It is suspected that, in the absence of crevices or heated surfaces on which concentrations of chlorides can occur, a high chloride concentration (several per cent) would be necessary to initiate cracking. The lowest metal temperature at which stress-corrosion cracking occurred was 80 C. Usu-

ally the metal temperature was 100C or higher. Annealing after fabrication was not effective in the prevention of stress-corrosion cracking. Service failures occurred in piping or equipment items of types 304, 304L, 316, 316L, 347, and 390 stainless steels.

(167) F. B. Snyder, T. A. McNary, and F. Eberle, "Investigation of Suitability of 18-8 (Type 304) Alloy for Superheater Service—With Respect to Corrosion and Stress-Corrosion Behavior in Chloride-Bearing Steam Condensate," Am. Soc. Mining, Metallurgical, and Petroleum Engrs., Paper No. 57-A-174 (1957). 17 pp.

An investigation of the possibility of using nonstabilized 18-chromium, 8-nickel type alloys as high-temperature superheater materials in place of the present practice of using stabilized 18-8 materials. Stress-corrosion tests in synthetic steam condensates containing 38.4 and 2000 ppm chloride showed that both stabilized and nonstabilized alloys suffered stress-corrosion cracking. No significant difference was observed in this respect between the two types of materials.

(168) I. Spiewak, and H. L. Falkenberry, "The Homogeneous Reactor Test Mockup," *Advances in Nuclear Engineering*, Am. Soc. Mechanical Engrs., Vol. 2, pp. 62–69 (1957).

During design and construction of the Homogeneous Reactor Test (HRT), some of its major components were assembled and operated on unenriched uranyl sulfate solution. A description of this mockup is presented and operational experience as related to design and operation of HRT is outlined. Major material of construction for both fuel and blanket systems is of type 347 stainless steel. The reactor core vessel is made of Zircaloy 2, the gas separator and certain parts of the circulating pump are made from titanium. Stress-corrosion cracking of 347 stainless steel occurred in several stagnant oxygen-depleted regions in contact with uranyl sulfate. Cracking was generally accompanied by precipitation of solids; no such phenomena were observed when oxygen concentration in main steam was maintained at a proper level. Tables, photos, diagrams.

(169) H. H. Uhlig, R. A. White, and J. Lincoln, Jr., "Austenitic Chromium-Iron-Nickel Alloys Resistant to Stress Corrosion Cracking in Magnesium Chloride," *Acta Metallurgica*, Vol. 5, No. 8, pp. 473–475 (1957). (In English.)

Reports on failure and resistance to failure by the stress-corrosion cracking mechanism, of chromium-nickel-iron stainless steels in boiling 42 per cent magnesium chloride. Laboratory heats of austenitic or ferritic compositions were prepared which did not crack within one week or more exposure to the test solution compared to cracking time of 1.5 hr for commercial type 304. Specimens were sheared strips, stressed beyond limit to form U, insulated from apparatus, spring loaded, and fully immersed in magnesium chloride. Plastic deformation at −196 C produces more cold-worked ferrite than deformation at higher temperatures; such cold-worked ferrite is more crack-resistant than untransformed austenite. A series of heats of high-purity 18-8 steel containing controlled amounts of nitrogen and carbon were tested. Those with less than 0.01 per cent carbon and 0.01 per cent nitrogen did not crack within 260 hr. With 0.15 per cent carbon or 0.15 per cent nitrogen, cracking time was 2.5 hr and 1.2 hr, respectively. Role of nickel in providing increased resistance to stress-corrosion cracking is discussed. Experiments demonstrate that a precipitation process is responsible for cracking susceptibility and that austenite-to-ferrite transformation is secondary. Crack direction is dictated by *bona fide* carbide or nitride precipitates, or by incipient precipitates at localized concentrations of interstitial atoms. Table shows effect of carbon, nitrogen and nickel on stress-corrosion cracking in magnesium chloride.

(170) W. L. Williams, "Chloride and Caustic Stress Corrosion of Austenitic Stainless Steel in Hot Water and Steam," *Corrosion*, Nat. Assn. Corrosion Engrs., Vol. 13, No. 8, p. 539t (1957).

The various factors which affect transgranular stress corrosion of austenitic stainless steels in steam-hot water systems are discussed. The evidence indicates that complete solution of the problem cannot be guaranteed through control of the alloy composition and condition, or through control of temperature and stress level within practical limits. Control of such factors and attention to design can reduce stress-corrosion hazards, but complete elimination apparently requires treatment of the environment to render it noncorrosive. The most serious troubles are in the steam phase in areas where intermittent wetting and steaming can cause concentration of water solids. Stress corrosion from chlorides is shown to be dependent on oxygen content, and prevention of damage from this source may be obtained by limiting either the chloride level or the oxygen level. Stress corrosion from caustic solutions is not so well understood, but preliminary information indicates that the maintenance of a proper phosphate-caustic ratio may be a suitable preventive measure.

(171) "Nuclear Power Problems," NRL-5084 (Progress Report, 1957), *Nuclear Science Abstracts* (U. S. Atomic Energy Commission), Vol. 12, p. 606 (1958).

Results of stress-corrosion experiments on type 347 stainless steel capsules containing NaCl solutions (500 to 530 ppm chloride) are summarized. Microscopic examination of the inside capsule surfaces showed evidence of localized attack in capsules containing H_2O_2.

(172) "Investigations Into Stress-Corrosion Cracking in Welded Gas Plant," *Gas Journal*, Vol. 292, p. 464 (1957); *Metals Review*, Vol. 31, p. 50 (1958).

Stress-relieving of welded components by Linde low-temperature process and control of liquor compositions are effective in preventing cracking.

(173) "Corrosion Studies," *Bettis Technical Review*, Volume 1, No. 3; *Nuclear Science Abstracts* (U. S. Atomic Energy Commission), Vol. 12, p. 22 (1957).

Results of an extensive investigation of chloride stress-corrosion testing of type 347 stainless steel steam generator tubing are presented. Experiments to determine the effect of corrosion of type 304 stainless steel with varying carbon content in reference primary coolant water are given.

1958

(174) E. B. Backensto and R. W. Manuel, "Corrosion in Cat Reformers With Naphtha Pretreaters," *Oil & Gas Journal*, Vol. 56, No. 20, pp. 131–135 (1958).

This paper includes the statement that transgranular stress-corrosion cracking of austenitic stainless steel by chlorides is being prevented by washing piping and exchangers with water and dilute alkaline solutions during shutdowns. Intergranular cracking of unstabilized austenitic alloy lining has occurred in one pre-treater reactor, probably as a result of polythionic acids formed by action of wet steam on sulfide scale, but has not occurred in units where stabilized alloys are used and contact of wet steam is avoided.

(175) E. Baerlecken and K. Lorenz, "Stress-Corrosion and Structure Formation of Austenitic Chromium-Nickel Steel X8 Cr-Ni-Mo-V-Nb 16/13," *Mitteilungen der Vereinigung der Grosskesselbesitzer*, No. 54, pp. 215–219 (1958); Abstracted in *Combustion*, Vol. 30, No. 5, p. 70 (1958).

Stress-corrosion cracks in austenitic steel caused by accidental addition of sodium chloride to feedwater were investigated. It was shown that the steel from one source containing less nitrogen than that from another source was more liable to stress corrosion and that the columbium-carbon ratio was a secondary factor. In addition to metallographic examination, the corrosion behavior of steels in fuming 65 per cent nitric acid has proved a valuable indicator of the factors contributing to the crack formation.

(176) P. Bastien, H. Veron, and C. Roques, "Special Steels Resistant to Stress-Corrosion by Hydrogen Sulfide," *Revue de métallurgie*, Vol. 55, No. 4, p. 301 (1958); Discussion p. 313.

A review of the principles of embrittlement of steels. Description is given of investigations of chromium-molybdenum-vanadium steels. Results of tests on hydrogen embrittlement and on corrosion under stress showed influence of cold working, composition, and mechanical properties of the steel. Steels used in tests include stainless steels and a 9.15 per cent nickel steel. The influence of chromium content on corrosion resistance of stainless steels was studied from the point of view of susceptibility to hydrogen and a scale of mechanical properties at which steels show greatest resistance to hydrogen was developed. It was found that 9 per cent nickel steel behaves very badly and that it is impossible to anneal it at high temperatures. A detailed study of the possibility of industrial heat treatment was carried out. Graphs, photomicrographs, tables.

(177) S. Berg, "Stress-Corrosion of Austenitic Stainless Steel," *Acciaio Inossidabile*, Vol. 25, p. 115 (1958); *Review Metal Literature*, Vol. 16, No. 4, p. 32 (1959).

Theories of mechanism of stress corrosion. Laboratory testing of steels of varying alloy content; influence of type of corrosive agent, concentration, pH, temperature, type and amount of stress, alloying elements, and structure of steel. Examples of stress corrosion of equipment in service. Nine references.

(178) W. O. Binder, "Stainless Alloys . . . Present and Future," *Chemical Engineering Progress*, Vol. 54, p. 45 (1958).

A review of present position of stainless alloys including latest developments in new alloys, theory, and practice. Stress corrosion is among the topics discussed.

(179) J. F. Bosich, "Corrosion Problems at an Alkali-Chlorine Plant," *Industrial and Engineering Chemistry*, Vol. 50, No. 7, p. 69A (1958).

Jigger screen hoppers, fabricated from type 403 stainless steel under high vibration, at 175 F, are used to separate the coarse from the fine milk of lime. The screens are cleaned daily by washing with a dilute solution of inhibited hydrochloric acid. Long hairline cracks developed in the stainless steel on the bottom after 6 weeks of operation. An attempt to weld the cracks was unsuccessful. By welding a steel plate, followed by painting with a glass-fiber reinforced neoprene lining substantially less down-time and a considerable reduction in buildup of lime was achieved.

(180) W. K. Boyd, "Observations on Stress-Corrosion Cracking of Austenitic Stainless Steels," Paper before NACE, North Central Section, Cincinnati (1958); Abstract, *Corrosion*, Nat. Assn. Corrosion Engrs., Vol. 14, No. 9, p. 79 (1958).

Case histories of a number of stress-corrosion cracking failures encountered in plant service are presented and discussed. Emphasis is placed on the type, extent and frequency of the cracking observed. Research techniques employed to establish that the failure is one of stress cracking also are described.

(181) W. K. Boyd and E. S. Bartlett, "Reactor Core Materials: Cladding and Structural Materials, Corrosion, Stainless Steels, Nickel-Base Alloys," *Technical Progress Review*, Battelle Memorial Inst., Vol. 1, No. 4, pp. 22, 23 (1958).

A description of the status of work on the mechanism of stress-corrosion cracking of stainless steel. Prefilming in uranyl sulfate - copper sulfate was found to give some protection from 50 ppm chloride level; sodium sulfite addition was also helpful. Higher nickel content of alloys give improved resistance to cracking in chlorides.

(182) R. G. Christman, et al, "Re-evaluation of Chrome Plated Hardened Type 410 Stainless Steel for Slip-on Stator Type Mechanism Motor Tube," WAPD-CTA (ME)-223; *Nuclear Science Abstracts* (U. S. Atomic Energy Commission), Vol. 12, p. 1614 (1958).

The Submarine Thermal Reactor Mark I Core-3 utilizes hardened type 410 stainless steel as primary coolant pressure boundary material in the motor tubes of all control rod drive mechanisms. Stress-corrosion data, other laboratory test data, and service performance data are reviewed and the suitability of the steel for this application is re-evaluated.

(183) R. E. Collins, "U.S. Expert Describes Italy's First Semichemical Mill," *Paper Trade Journal*, Vol. 142, No. 1, pp. 24–29 (1958).

Description of Societa per Azioni Fabriche Fiammiferi Ed Affini's semichemical mill in Magenta, Italy. Rotary digesters are made of mild steel. Lining digesters with stainless steel proved unsatisfactory due to stress cracking at plug welds so metallizing with stainless was tried. Process piping is either rubber-lined, lead or stainless steel. Pulp is discharged from top of tower by a rotary plow into a stainless steel screw conveyor. Caustic and bleach liquor are pumped to stainless steel head boxes that maintain constant heads on rotameters supplying caustic and bleach to caustic and hypochlorite stages.

(184) C. Edeleanu, "The Intercrystalline Corrosion of Stainless Steels," *Chemistry and Industry*, No. 42, pp. 1360, 1371 (1958).

Intercrystalline corrosion of austenitic steels is generally assumed to be the consequence of carbide precipitation in the steel and is successfully controlled either by heat treatment or by stabilization of the steels with titanium or columbium. However, there are at least three cases in which intercrystalline failures are known to occur in steels which have been properly stabilized or in which the normal explanation cannot be applicable. One case is intercrystalline corrosion found in steel in caustic solutions at elevated temperatures. It seems that conditions leading to this type of failure can arise in plants using reasonably high purity waters, provided that there is a heavy heat flux through the steel and the design is such as to allow concentration effects to occur. A second type of intercrystalline failure occurs with low carbon 18-8 molybdenum steel. It was found that what appears to be intercrystalline stress corrosion occurs in concentrated chloride solutions such as 42 per cent magnesium chloride. Intercrystalline corrosion has also been found with austenitic alloys in fused chloride. This type of cracking is again believed not to be the preferential leaching of the chromium by the salt. It appears therefore that there are at least three types of intercrystalline corrosion associated with the austenitic stainless steel which are not due to lack of stabilization and cannot therefore be avoided by merely insuring that the steel is not susceptible to intercrystalline corrosion in the conventional copper sulfate or nitric acid test.

(185) F. W. Emhardt, "Corrosion—Here and There," *Industrial and Engineering Chemistry*, Vol. 50, pp. 71A, 72A (1958).

General discussion of corrosion and stress-corrosion problems in chemical and power plants. Some case histories.

(186) J. P. Fraser, G. G. Eldredge, and R. S. Treseder, "Laboratory and Field Methods for Quantitative Study of Sulfide Corrosion Cracking," *Corrosion*, Nat. Assn. Corrosion Engrs., Vol. 14, p. 517t (1958).

Apparatus and quantitative procedures for sulfide corrosion cracking tests have been deveveloped. Statistical techniques of probit analysis have been adapted for use with cracking test data so as to make optimum use of minimum number of tests. Analysis of laboratory data yields a number which is called the critical strain, S_c. This is the strain at which the probability of failure under specific test conditions used is one half. Very susceptible steels have low S_c values whereas nonsusceptible steels have high S_c values. Critical strain is a function not only of the alloy tested, but also of test environment and procedure. It is lowered by addition of acids and CO_2. Using alloys of varying S_c values, all tested at the same strain, the relative severity of any given test environment (for instance, flow from sour gas well) can be measured. Analysis of data from field tests yields a severity rating, R_s, which is the critical strain of an alloy which would give 50 per cent failures in test. High R_s values are associated with severe test conditions. The general method may be adaptable to other stress-corrosion systems. Data are presented for 5-9 nickel steel and 9-12 chromium steel but not 18-8 steel, among others. Photos show laboratory and field stress-corrosion cracking specimen holders.

(187) G. E. Galonian, "Results of Stress-Corrosion Tests of Type 347 Stainless Steel in 500 F pH 10–11 Lithium Hydroxide," KAPL-M-GEG-11, May 2, 1958; *Corrosion*, Nat. Assn. Corrosion Engrs., Vol. 15, No. 6, p. 110a, (1959).

The results of stress-corrosion tests of type 347 stainless steel in 500 F, 10–11 pH lithium hydroxide are described. Stressed-bolt specimens heated to 626, 665 and 695 F to produce boiling were exposed for 4 weeks to determine the extent of corrosion to be expected. Also, tests were made to evaluate corrosion under conditions of leakage to the atmosphere.

(188) M. A. Golik and I. H. Welinsky, "Preliminary Evaluation of the Cracking Tendencies of Hardened Type 410 Stainless Steel," (Incl. Min. of Meeting—Corrosion Studies on Hardened AISI 410 Steel); WAPD-CTA(MEE)-421; *Nuclear Science Abstracts* (U. S. Atomic Energy Commission), Vol. 12, p. 2141 (1958).

The current activities on the investigation of stress-corrosion cracking of hardened type 410 stainless steel are reviewed.

(189) M. A. Golik, "Stress-Corrosion Cracking of Type 410 Stainless Steel-Miniature Motor Tube Test Program," WAPD-CTA (MEE) (1958); *Nuclear Science Abstracts* (U. S. Atomic Energy Commission), Vol. 12, p. 1614 (1958).

Stress-corrosion cracking of chrome-plated, hardened 410 stainless steel tempered at 650 F in submarine reactor cooling water was investigated. Differences between laboratory testing conditions and actual service make it necessary to redesign a new test specimen, which more closely simulates motor tube geometry.

(190) Ludwig Graf, "Stress-Corrosion," *Draht*, No. 9, pp. 383–399 (1958); *Review of Metal Literature*, Vol. 16, No. 1, p. 44 (1959).

Stress-corrosion sensitivity of supersaturated alloys with precipitation tendency can be eliminated by heat treatment, provided the alloy is not corrosion sensitive in the homogeneous state of saturation. With unsupersaturated homogeneous al-

loys, stress corrosion was observed only when the alloying components of the solid solution were considerably more negative than the base metal. Nineteen references.

(191) H. Gräfen, "The Influence of Surface Layers on Stress-Corrosion in Steel," *Archiv Eisenhüttenwesen*, Vol. 29, p. 225 (1958).

An investigation, using apparatus specially developed by the author, of stress corrosion in steels, with particular emphasis on the role of surface layers such as oxide films. Supporting data are given on plain, low-alloy nickel-chromium-molybdenum and austenitic steels exposed to solutions containing potassium dichromate, nitrate, and halide additions.

(192) E. A. Gulbransen, "New Ways to Look at Corrosion Processes," *Chemical Engineering Progress*, Vol. 54, No. 11, p. 60 (1958).

This paper includes an electron micrograph of the corrosion product formed by stress-corrosion of type 304 stainless steel exposed at 600 C (1112 F) in wet oxygen plus a trace of hydrogen chloride. The corrosion product consists of platelets of chromic oxide (Cr_2O_3), which are single crystals.

(193) Norman Hackerman, Ray M. Hurd, and Earl S. Snavely, "Corrosion Rates of Mild Steel in Aqueous Ammonium Nitrate Solutions," *Corrosion*, Nat. Assn. Corrosion Engrs., Vol. 14, p. 203t (1958).

(194) J. Halbig and O. B. Ellis, "Observations on Corrosion Resistance of High Strength Stainless Steels for Aircraft," *Corrosion*, Nat. Assn. Corrosion Engrs., Vol. 14, No. 8, p. 389t (1958).

In the discussion on the corrosion performance of Armco 17-7 PH and PH 15-7 molybdenum steels, stress corrosion is mentioned. Stressed specimens have not cracked in the mild industrial atmosphere at Middletown, Ohio, but cracking has occurred in a marine atmosphere.

(195) J. G. Hines and T. P. Hoar, "Stress-Corrosion Cracking of Austenitic Stainless Steels With Applied EMF," *Journal of Applied Chemistry*, No. 8, p. 764 (1958); *Review of Metal Literature*, Vol. 16, p. 47 (1959).

Behavior of chromium-nickel austenitic stainless steel in 42 per cent aqueous magnesium chloride solution at 150 to 154 C, saturated with air, was studied under conditions of cathodic or anodic treatment of the metal during the induction period prior to crack initiation and during crack propagation. Mild cathodic polarization delays the onset of cracking and fracture, the time to fracture increasing with increasing degree of polarization.

(196) T. P. Hoar and J. G. Hines, "Proceedings of the 8th Meeting of the International Committee for Electrochemical Thermodynamics and Kinetics," Madrid, 1956, p. 273, Butterworths, London (1958).

(197) T. P. Hoar and J. M. West, "Mechanicochemical Anode Solution," *Nature*, Vol. 181, p. 835 (1958).

(198) L. R. Honnaker, "Stainless Steels for Corrosion Resistance," *Chemical Engineering Progress*, Vol. 54, No. 1, pp. 79–82 (1958).

To realize optimum performance of stainless steel equipment, attention is now being directed to minimize failures that result from pitting, crevice corrosion, intergranular corrosion, stress-corrosion cracking and related phenomena where general corrosion is actually slight. Causes and means of avoiding such types of failures are discussed. Design features that will insure free drainage, ease of cleaning and elimination of crevices will help to avoid pitting and crevice corrosion. Where acidic conditions are to be handled above ambient temperatures, consideration should be given to the necessity and means of avoiding intergranular corrosion.

(199) J. P. Hugo and L. G. Nel, "Failure of Type 316 Stainless Steel Autoclave Components," *Corrosion*, Nat. Assn. Corrosion Engrs., Vol. 14, p. 553t (1958); Vol. 15, pp. 373t–381t (1959).

An investigation into the cause of failure of a number of type 316 autoclave components that failed in service after extremely short operational life (38 to 52 hr). The body and cover of the autoclave in question were of monel while its cooling coil, thermowell, sampling tube, valve, and associated fittings were of type 316. Runs were made with distilled water at 150 to 300 C at pressures up to 1300 psi; one run was made with 10 per cent sodium hydroxide solution. Failure of these components situated in the vapor phase was attributed to stress-corrosion cracking. The active corrodent was probably chloride, while the stresses that initiated failure were predominantly residual. The components used suffered some degree of cold working prior to installation. Failure was in no way due to excessive operating temperatures or pressures. Macro- and microphotographs are included.

(200) J. R. Hunter, "Application of Type 410 Stainless Steel in Control Rod Drive Mechanism Motor Tubes and Outer Housing," WAPD-CTA(ME)-250 (OTS); *Nuclear Science Abstracts* (U. S. Atomic Energy Commission), Vol. 12, p. 1568 (1958).

Results of laboratory testing of stress-corrosion cracking properties of type 410 stainless steel are presented. This material was evaluated for control rod drive mechanism motor tubes and outer housing.

(201) K. W. Leu and J. N. Helle, "On the Mechanism of Stress Corrosion of Austenitic Stainless Steels in Hot Aqueous Chloride Solutions," *Corrosion*, Nat. Assn. Corrosion Engrs., Vol. 14, No. 5, p. 59 (1958) (p. 249t).

An investigation of the mechanism of transcrystalline stress corrosion of austenitic stainless steels (18-8 and 25-20) in hot aqueous chloride solutions shows this phenomenon is a process alternating between corrosion and mechanical cracking. Sharp-edged pits formed by corrosive attack initiate and propagate mechanical cracking, which is of brittle nature. Pits act as stress-raisers to produce notch brittleness in materials involved. At low stresses only long pits at slipbands initiate cracking while at high stresses small pits at slipbands or grain boundaries may cause it. The investigation proves also that initial corrosive attack depends principally on the physical and chemical behavior of the passivating film already on the steel or formed during exposure to the environment, and only to a minor degree on metal structure. If the type of initial corrosion is changed by comparatively small alterations in composition of the corrosive medium, stress corrosion is either prevented or accelerated. Tests illustrating this are discussed.

(202) E. A. Livingstone, "The Atomic Age Challenge to Steel," *Journal of Metals*, Vol. 10, p. 111 (1958).

This paper includes the statement that stress-corrosion cracking difficulties induced by chlorides carried into the system on improperly cleaned stainless steel recently caused a setback of one year on the experimental homogeneous reactor program. The problem of stress-corrosion cracking may be overcome by use of type 430 (15 chromium-1 nickel); another possibility lies in vacuum-melted stainless steel with extremely low carbon and nitrogen.

(203) H. L. Logan, "Studies of Stress-Corrosion Cracking of Austenitic Stainless Steel," *Welding Journal*, Am. Welding Soc., Vol. 37, No. 10, p. 463s (1958).

Stress-corrosion cracking of type 304 stainless steel was produced by stressing sheet tension specimens to room temperature yield strength in boiling 0.5 N sodium chloride, 0.1 N sodium nitrite aqueous solution. Accelerated cracking of stressed specimens is accomplished by making them anodes with applied external current density of 0.03 to 1.0 ma per sq cm. Cathodic current densities of 0.04 ma per sq cm or more protected material against stress-corrosion cracking. Material stressed to room-temperature yield strength in boiling solution continued to extend plastically (but nonuniformly) for at least 1 hr after load was applied. Macroscopic evidence of corrosion of type 304L specimens, immersed unstressed in normal solutions of boiling ferrous chloride, ferric chloride, ferrous chloride plus hydrochloric acid, nickel chloride, chromic chloride, and manganous chloride, was found only in those exposed in ferric chloride solutions with a pH of <5 and in ferrous chloride plus hydrochloric acid with a pH of 1.3. It is postulated that stress-corrosion cracking is electrochemical in its inception and in part, at least, in its propagation. Sporadic but repeated creep of material in certain favorably oriented regions ruptures the protective film in narrow areas, normal to applied stress. The film-free area is a small anode; the cathode area is very large and corrosion is rapid until film re-forms. This eventually produces condition of stress concentration, normal to applied stress that plays an important part in propagation of stress-corrosion cracking. Graphs.

(204) T. Marshall, "Stress Corrosion of Austenitic Stainless Steel in Geothermal Steam," *Corrosion*, Nat. Assn. Corrosion Engrs., Vol. 14, No. 3, p. 59 (1958) (p. 195t).

Stress-corrosion tests on austenitic stainless steels were conducted in geothermal steam contaminated with chlorides, hydrogen sulfide, carbon dioxide, etc., under the following steam conditions: (1) Air-free steam superheated at 150 C, and (2) steam superheated and aerated at 150 C. Stress-corrosion cracking occurred readily in the aerated, superheated steam, but did not occur at all in the air-free, superheated steam. These test results provide experimental confirmation of Hoar and Hines' theory that the cathodic depolarizing action of oxygen is essential to the stress-corrosion mechanism. For comparison purposes corrosion-rate data, and stress-corrosion data on other alloys in the steam are given. Factors controlling the stress corrosion of austenitic stainless steel in geothermal steam are discussed.

(205) P. S. Otten, "How Tubes Compare for Nuclear Reactor Boilers," *Power*, Vol. 102, No. 1, pp. 80, 176, 178, 180; No. 2, p. 80 (1958).

This paper discusses the choice of fabricated materials for steam generators heated by gas-cooled reactors and experiences with waste-gas heated boilers in industrial applications. Primary coolant gases usually used in reactors do not corrode most metals, even at fairly high temperatures. At above 840 F and high pressures, hydrogen gradually combines with carbon in steel to form methane, making steel unsatisfactory as a container. Above 1020 F this process accelerates rapidly. Nitrogen nitrides and embrittles steel and alloy steels above 1000 F. Steam and water at high temperatures can seriously corrode metals unless carefully treated to reduce oxygen content. Chloride and oxygen must be kept at an absolute minimum to prevent chloride stress corrosion of austenitic stainless materials. Type 316 stainless and Inconel have excellent elevated creep properties for parts exposed to gas only. They can be used in final-stage superheating up to 900 F. Designs described are based on use of carbon steel for metals below 800 F, and $2\frac{1}{4}$ Cr - 1 Mo for temperatures up to 1100 F. Austenitic stainless steel and Inconel are considered between 1000 and 1500 F.

(206) H. W. Paxton, R. D. Leggett, and R. H. Reed, "Stress-Corrosion Cracking of Single Crystals of Stainless Steel," Preprint, Am. Inst. Mining, Metallurgical, Petroleum Engrs., Conference, (1958).

Single crystals of austenitic steels with approximate composition 18 chromium-8 nickel and 20 chromium-20 nickel and of a ferritic steel containing 20 per cent chromium have been grown. Single crystals were stressed in tension in boiling magnesium chloride. The aim of the experiments was to try to distinguish between the various proposed theories of stress corrosion by utilizing the special advantage of single crystals.

(207) E. H. Phelps, "Stress-Corrosion in Metals," *Product Engineering*, Vol. 29, No. 31, p. 56 (1958).

A discussion of stress level, chemical environment, and time of exposure as the three elements involved in stress-corrosion cracking. The author describes intergranular and transgranular types of stress-corrosion and enumerates design countermeasures. These include selection of material, avoiding built-in crevices and conditions leading to pitting, use of stress relief, avoidance of high thermal stresses in service, control of chemical environment, use of shotpeening or cathodic protection in difficult applications, and avoidance of careless handling of work-hardenable metals. The table lists harmful environments for austenitic stainless steels, brass, aluminum-magnesium, steel, and manganese-aluminum.

(208) J. H. Phillips and W. J. Singley, "Chloride Stress-Corrosion Inhibitor Program," *Corrosion*, Nat. Assn. Corrosion Engrs., Vol. 14, No. 9, p. 79 (1958) (Abstract).

A series of screening tests was run in tilting autoclaves to evaluate the performance of selected potential inhibitors in preventing chloride stress-corrosion attack of type 347 austenitic stainless steel in alkaline-phosphate boiler water containing 50 or 500 ppm chloride. The tests were conducted at a temperature of 500 F and saturation pressure. On the basis of the screening test results, a number of the more promising inhibitors was tested further to evaluate concentration effects. Of the chemicals tested, nitrate appears to be a satisfactory inhibitor for boiler application. Sodium sulfite also effectively prevents chloride stress-corrosion cracking by scavenging oxygen.

(209) L. E. Phillips, "Autoclave Testing of Type 304 Stainless Steel," The Martin Company, MND-E-1322 (1958).

U-bend test specimens were subjected to corrosive water in rocker autoclaves, both in the vapor and the water phases. It was found that oxygen and chlorides were the only variables contributing to the cracking. Results indicate that a high oxygen level will not allow cracking at lower chloride levels and conversely. The minimum oxygen level inducing cracking was 4 per cent. Oxide film formation on the steel may be sufficient to induce corrosion cracking, even in low oxygen concentrations. Since a surprisingly high concentration of oxygen was necessary to cause cracking, it is suggested that, with adequate deaeration, untreated water may be used safely in boilers.

(210) F. J. Poss, "What You Can Do to Reduce Stress-Corrosion," *Chemical Engineering*, Vol. 15, p. 140 (1958).

To reduce stress corrosion of stainless steel in plants established design practices for high temperature equipment should be followed (piping stress analysis); dead ends or traps should be avoided or periodically flushed; careless handling of parts should be avoided to prevent work-hardening; cleaning agents that could be employed as pickling solutions should not be used; heating and cooling of stainless sections should be done gradually to prevent the creation of thermal stresses; lagging should be kept on high temperature lines and fittings, and they should be kept dry.

(211) V. V. Romanov and V. V. Dobrolyubov, "Effect of Cathodic and Anodic Polarization on the Rate of Stress-Corrosion of Austenitic Stainless Steel," *Metallovedenie i Obrabotka Metallov*, No. 7, p. 19 (1958).

Cathodic and anodic polarization curves for the stress corrosion of an 18-9 chromium-nickel steel in boiling 42 per cent magnesium chloride were plotted. An effect of polarization on the nature of the corrosion cracks was established by metallography. An explanation is given of the shape of the cathodic and anodic polarization curves from the polarization diagram for stress corrosion and by the observations on the effect of polarization on the shape of the cracks. Photomicrographs.

(212) A. V. Riabchenkov and E. L. Kasimirovskaya, "Fatigue Strength of Austenitic Steels Exposed to Corrosive Cases at High Temperatures," *Metallovedenie i Obrabotka Metallov*, p. 6 (1958); Brutcher Translation No. 4164.

Study of the effect of high-temperature gas corrosion on the endurance limit of gas turbine blade materials. Data on scaling behavior and endurance limits of two austenitic stainless steels in dry air containing various amounts of sulfur dioxide and in air containing sulfur dioxide and water vapor, at 650 C.

(213) A. V. Riabchenkov, et al, "Microelectrochemical Method for the Study of the Corrosion under Stress of Metals," *Zavodskaya Laboratoriya*, Vol. 24, pp. 167–178 (1958); *Nuclear Science Abstracts* (U. S. Atomic Energy Commission), Vol. 13, No. 10, p. 1216 (1959).

A description is given of an installation designed for the electrochemical study of localized regions of a metal subjected simultaneously to a corrosive medium and a tensile stress. The stress corrosion of cast iron and several steels was investigated in 0.01 N HCl solutions with 0.09 per cent H_2O_2, and the electrode potential was measured. The results show that static stresses displace the electrode potential of steel to more negative values. It was established that the potential of the grain boundary is more negative than the potential of the grain body.

(214) L. R. Scharfstein and W. F. Brindley, "Chloride Stress Corrosion Cracking of Austenitic Stainless Steel Effect of Temperature and pH," Paper presented before Nat. Assn. Corrosion Engrs., Fourteenth Annual Conference, San Francisco, Calif., March 17–21, 1958. Abstracted in *Corrosion*, Nat. Assn. Corrosion Engrs., Vol. 14, No. 1, p. 107 (1958).

Overstressed U-bends of types 304 and 347 stainless steels were exposed to water containing 5 to 550 ppm chloride ion at temperatures of 165, 185, 200, and 500 F. The pH was controlled at 6.5 to 7.5 and 10.6 to 11.2. Examination of specimens was made to ascertain the initiation of cracks. At high pH, cracks appeared at the edges with little evidence of pitting; at the neutral pH, cracks were found both at edges and associated with pits. Oxygen content of the water was an important variable, especially in its effect in accelerating pitting of stainless steel. Sensitized type 304 stainless steel had longer and deeper cracks than annealed types 304 and 347 in the same exposure time. Where boiling or alternate wetting-and-drying of the stainless steel U-bends did not occur, chloride stress-corrosion cracking of the U-bends was prevented by alkaline phosphate treatment.

(215) L. E. Scharfstein and W. F. Brindley, "Chloride Stress-Corrosion Cracking of Austenitic Stainless Steel—Effect of Temperature and pH," *Corrosion*, Nat. Assn. Corrosion Engrs., Vol. 14, p. 588t (1958).

Overstressed U-bends of 304 and 347 stainless steels were exposed to water containing chloride ions to determine the

susceptibility of those steels to stress-corrosion cracking between 165 and 200 F; pH was controlled at 6.5 to 7.5 and 10.6 to 11.2 for the tests. At the high pH crack appeared at the edges, with little evidence of pitting. At the neutral pH cracks were found at the edges and associated with pits. It is concluded that chloride stress-corrosion cracking in the test range is less severe than at 500 F. Specific conditions are required.

(216) G. Shinoda, T. Sano, and T. Kawasaki, "Corrosion Characteristics and Change in Mechanical Properties of Some Austenitic Stainless Steels in Uranyl Salt Solution," *Journal*, Japan Inst. Metals, Vol. 22, No. 10, p. 500 (1958).

In this paper it is mentioned that the effect of mechanical stress on the corrosion resistance was investigated by autoradiography of the corroded specimens. Resistance to stress corrosion of the 316L specimens containing molybdenum and copper was inferior to that of the specimen containing columbium. Corrosion resistance of columbium stainless steel seemed scarcely to be influenced by applied stress.

(217) V. P. Sidorov and A. V. Riabchenkov, "Stress-Corrosion Cracking of Austenitic Steels at High Temperatures and Pressures," *Metallovedenie i Obrabotka Metallov*, No. 6, p. 25 (1958); Brutcher, Translation No. 4250.

Description of a new method of testing austenitic steels for long-time corrosion-resistance in aqueous solutions at high temperatures and pressures. Three austenitic steels were investigated, containing 10 to 15 per cent nickel and 14 to 18 per cent chromium with small amounts of other elements. All three steels were subject to stress-corrosion cracking in alkaline solutions, with mainly transcrystalline fracture. In distilled water at 100 C with access of oxygen only 15-15 steel was attacked. No stress-corrosion cracking occurred in distilled water at 300 C and restricted oxygen supply, or in solutions of sodium chloride, trisodium phosphate, disodium phosphate, sodium sulfate, and sodium sulfite in absence or a limited supply of oxygen. Critical concentrations of alkaline solutions depend on temperature and pressure. Stress-corrosion cracking inhibiting effect of sodium chloride additions to alkaline solutions was studied. The exponential character of curves of time-to-rupture *versus* absolute temperature of alkaline solutions is discussed. Heat treatment has no direct effect on tendency to stress-corrosion cracking but may prevent it by eliminating internal stresses.

(218) P. P. Snowden, "Intercrystalline Stress-Corrosion Cracking of Austentic Stainless Steel in Caustic Solutions," *Chemistry and Industry*, No. 51, p. 1692 (1958).

Very rapid stress-corrosion attack of austenitic stainless steels can occur with caustic solutions as dilute as 1 per cent by weight. Attack takes the form of intercrystalline cracking which can cause fracture of specimens stressed to 10 tons per sq in. in a few hours at 300 C. Intercrystalline cracking was observed for both potassium hydroxide and sodium hydroxide. In high pressure steam, however, potassium hydroxide contaminated specimens show intercrystalline cracking. Addition of sodium silicate to sodium hydroxide contaminating the specimen exposed to high steam pressures causes cracking to become wholly intercrystalline. Reduction of any of three main variables, stress, concentration, and temperature, reduces rate of attack but complete freedom from attack cannot be achieved without reduction of all three.

(219) R. W. Staehle, F. H. Beck, and M. G. Fontana, "Mechanism of Stress-Corrosion of Austenitic Stainless Steels in High Temperature Chloride Waters," Ohio State University Research Foundation, Technical Report No. 2 (1958). Also see: *Corrosion*, Nat. Assn. Corrosion Engrs., Vol. 15, No. 7, p. 373t (1959).

Stress-corrosion cracking of austenitic stainless steels was studied under various conditions of stress, chloride concentration, complete immersion of specimens, intermittent wetting and drying, and presence of oxygen. Stress-corrosion cracking will occur at stresses as low as 2000 psi at 50 ppm NaCl. A three-dimensional analysis of stress-corrosion cracks was made and a mechanism of cracking proposed.

(220) H. H. Uhlig and J. Lincoln, Jr., "Chemical Factors Affecting Stress-Corrosion Cracking of 18-8 Stainless Steels," *Journal*, Electrochemical Soc., Vol. 105, pp. 325–332 (1958).

Transgranular stress-corrosion cracking of 18-8 type 304 specimens in boiling 42 per cent magnesium chloride does not depend on rate of stressing (less than 1 sec to 10 min) nor on small variations in degree of plastic deformation. Cold-worked specimens fail in shorter times than annealed, sheared specimens. Addition of hydrochloric acid to magnesium chloride decreases cracking time whereas addition of sodium hydroxide increases the time. Pre-exposure of unstressed specimens to magnesium chloride slightly decreases cracking times of the same specimens subsequently stressed. Cracks occur along sheared edges of unstressed specimens despite stress relief anneal at 375 C for 2 hr.

Cracks propagate along sheared edges of U-bend specimens at 0.5 to 1 cm per hr through that portion of the specimen cross-section in tension, the rate being much slower through the remaining cross-section. No induction time for cracks to initiate was observed.

Sizeable pits are not necessary for cracking in magnesium chloride but appear to be essential in media like sodium chloride which in absence of pitting is not particularly active in causing cracking. The pitting mechanism produces concentrated low pH metal chlorides (for example, ferrous chloride) within the pit, which like magnesium chloride cause immediate cracking. Oxygen is required for pitting of 18-8 steel by sodium chloride solutions as shown by Uhlig and Morrill, and hence also for stress-corrosion cracking as observed by Williams and Eckel, but oxygen is not necessary in magnesium chloride or ferrous chloride.

Cracking can be prevented by cathodic protection at a current density of 0.03 ma per sq cm or higher. Anodic current density up to 0.01 ma per sq cm were found to have no effect on cracking tendency, nor did coupling of 18-8 steel to platinum.

(221) J. N. Wanklyn and D. Jones, "The Intercrystalline Corrosion of Stainless Steel in Alkaline Solutions," *Chemistry and Industry*, No. 28, pp. 888, 889 (1958).

Stainless steels, 18-8, stabilized with either columbium or titanium were exposed as heat-transfer specimens to boiling potassium hydroxide solutions at a pH of 11 at 280 C (536 F). When stressed to 20,000 psi they did not crack. When formed into specimens with crevices allowing concentration of the caustic, they cracked intergranularly within 200 hr. Sealed tubes containing 10, 25, and 50 per cent potassium hydroxide placed in a furnace at 325 C (617 F) and stressed by the steam pressure failed within 200 hr by a combination of trans- and intercrystalline cracking.

(222) "Homogeneous Reactor Project Quarterly Progress Report," Atomic Energy Commission ORNL-2654 (1958); *Nuclear Science Abstracts* (U. S., Atomic Energy Commission). Vol. 13, No. 9, p. 1120 (1959).

The effect of cold work and heat treatment on corrosion resistance of type 347 stainless steel was investigated. Phosphate and fluoride ions partially inhibited stress-corrosion cracking of 347 stainless steel in chloride-containing water at 200 C. The effect of UO_2^{2+} on stress-corrosion cracking of 347 stainless steel in chloride-containing UO_2SO_4 solutions was studied. Various treatments to prevent cracking of wrought type 347 stainless steel U-bend specimens in chloride- and oxygen-containing water at 300 C were tried. Cast 347 steel shows no cracking in $MgCl_2$ or in chloride-containing water.

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(223) R. Benes, F. J. Holsinger, and R. E. Pierson, "Corrosion in the Corn Wet Milling Industry," *Corrosion*, Nat. Assn. Corrosion Engrs., Vol. 15, p. 113t (1959).

Stress-corrosion cracking of type 316 evaporator tubes is mentioned in connection with sugar and corn syrup production.

(224) H. R. Copson, "Effect of Composition of Stress-Corrosion Cracking of Some Alloys Containing Nickel," Physical Metallurgy of Stress-Corrosion Fracture (T. N. Rhodin), Metallurgical Society of AIME, Metallurgical Society Conferences, Vol. 4, Interscience Publishers, Inc., New York, N. Y. (1959).

A series of alloys was prepared with the nickel content ranging from 8 to 80 per cent with the cromium held at 16 to 20 per cent and with the balance essentially iron. These were drawn to wire, loaded in tension, exposed to boiling 42 per cent magnesium chloride solution and the time to cracking observed. The specimens with 8 per cent nickel broke within an hour. The time to cracking increases rapidly with nickel content and alloys with more than 45 to 50 per cent nickel seemed immune to cracking. (Also Reference (244))

(225) C. Edeleanu, "Propagation of Stress-Corrosion Cracks," Physical Metallurgy of

Stress-Corrosion Fracture (T. N. Rhodin), Metallurgical Society of AIME, Metallurgical Society Conferences, Vol. 4, Interscience Publishers, Inc., New York, N. Y. (1959).

The mechanism of stress-corrosion cracking is assumed to be broadly similar in all cases and that there are only differences in detail from case to case. This paper supports the view that the cracks progress in short brittle bursts in the case of alpha brass in ammonia, and it is postulated that the function of corrosion is to assist in the initiation of brittle fracture and not to cause appreciable penetration.

(226) J. P. Engle, G. L. Floyd, and R. B. Rosene, "Chloride Stress-Corrosion Cracking of the Austenitic Stainless Steels," NACE Technical Committee Report 59-5; *Corrosion*, Nat. Assn. Corrosion Engrs., Vol. 15, p. 69t (1959).

The active-passive characteristics of the alloys play an important role which probably has not been understood previously. A number of factors, acting together, must be present to produce cracking. Indications are that cracking occurs in neutral chloride solutions when passivity is destroyed at localized areas of film-breakdown. If the entire surface is activated, as in the presence of hydrochloric acid, no cracking results. Figures.

(227) J. E. Finsen, "Controlling Corrosion in a Modern Magnesia-Base Sulfite Mill," *TAPPI*, Tech. Assn. Pulp and Paper Inst., Vol. 42, p. 104 (1959).

It is mentioned that stress-corrosion cracking occurred in acid and liquor piping where frequent abrupt temperature changes occur, and in locations where hydraulic pulsations set up vibration in piping; at present stress is the only variable that can be controlled if chlorides cannot be eliminated.

(228) J. G. Hines and R. W. Hugill, "Metallographic and Crystallographic Examination of Stress-Corrosion Cracks in Austenitic Cr-Ni Steels," Paper by Imperial Chemical Industries Ltd., England (1959). 19 pp.

Stress-corrosion cracks in austenitic chromium-nickel steel wires have been examined at different stages of their development using various techniques. It is found that crack development can be divided into two stages: the formation of fine cracks which spread sideways faster than they penetrate into the material; and the formation of larger open cracks which are extensively branched and which form from fine cracks after yielding has begun ahead of the crack.

(229) W. W. Kirk, F. H. Beck, and M. G. Fontana, "Stress-Corrosion Cracking of Austenitic Stainless Steels in High Temperature Chloride Waters," Physical Metallurgy of Stress-Corrosion Fracture (T. N. Rhodin), Metallurgical Society of AIME, Metallurgical Society Conferences, Vol. 4, Interscience Publishers, Inc., New York, N. Y. (1959).

Stress-corrosion cracking of austenitic stainless steels was studied under various conditions of stress, chloride concentration, temperature, time, and intermittent wetting and drying of the specimen. Specimens of types 347, 316, and 304 stainless steel will crack at stress as low as 2000 psi at 50 ppm NaCl. Reduced temperatures increase the time necessary for the onset of cracking but have no effect on the stress necessary to produce cracking. A proposed mechanism of stress-corrosion cracking is based on periodic progression of a crack plus the contributions of stress and electrochemical dissolutions.

(230) R. E. Lochen and E. R. Miller, "Resistance to Stress-Corrosion of 12 per cent Chromium Stainless Steel," *Industrial Engineering Chemistry*, Vol. 51, p. 763 (1959).

Stress-corrosion tests of 12 per cent chromium stainless steel (types 403, 422) were made in 0.5 per cent acetic acid saturated with hydrogen sulfide. For the materials tested, resistance to stress corrosion increased with increasing tempering temperature over 1000 F, additions of secondary alloying elements (0.5 per cent molybdenum instead of 0.05 per cent; 1 per cent molybdenum, 1 per cent tungsten, 0.2 per cent vanadium, 0.8 per cent nickel), decrease in hardness, vapor-blasted rather than as-ground finish.

(231) R. L. McGlasson and W. D. Greathouse, "Stress-Corrosion Cracking of Oil Country Tubular Goods," *Corrosion*, Nat. Assn. Corrosion Engrs., Vol. 15, p. 88 (1959).

A brief review of the general problem is given with a consideration of hydrogen embrittlement. A list is presented of material-environment combinations resulting in cracking. Sulfide corrosion cracking and sweet corrosion cracking are considered, with a review of the literature on the subject. A new test method is explained, which uses a notched ring of the material loaded to different percentages of the yield deformation. Data on hardness, applied stress, and time-to-failure are given from tests conducted by the new method.

(232) J. W. McGrew, "Autoclave Testing of Type 430 Stainless Steel," Atomic Energy Commission, MND-E-1602 (1959); *Nuclear Science Abstracts*, Vol. 13, p. 613 (1959).

U-bend specimens are not susceptible to stress corrosion cracking in up to 100 per cent O_2, chloride concentrations to 1100 ppm, pH adjusted to 11.5 with NaOH, temperatures up to 400 F and periods up to 1176 hr in a rocker-type autoclave. No cracking occurred in magnesium chloride at 1030 ppm chlorine. Pitting corrosion occurs in greater than 100 ppm chlorine concentrations combined with approximately 20 per cent oxygen. Croloy 16-1 will resist stress and pitting corrosion under these conditions. Stress-corrosion cracking of 430 does occur in certain conditions, usually at low pH values.

(233) C. R. McKinsey, "Effect of Low-Temperature Stress Relieving on Stress-Corrosion Cracking," *Revue de la soudure*, Vol. 14, p. 42 (1958) (In French); *Corrosion*, Nat. Assn. Corrosion Engrs., Vol. 15, p. 104a (1959).

Welded structures are susceptible to stress corrosion because of the residual stresses that are generally present. A series of tests for determining the effect of low-temperature stress relieving on the stress corrosion of arc butt welded steel plates showed that stress corrosion increases with decrease in carbon content and that controlled relieving at low temperature reduces susceptibility of welded plates to stress corrosion. Eleven references.

(234) N. A. Nielsen, "The Role of Corrosion Product in Stress-Corrosion Cracking of Austenitic Stainless Steel," Physical Metallurgy of Stress-Corrosion Fracture (T. N. Rhodin), Metallurgical Society of AIME, Metallurgical Society Conferences, Vol. 4, Interscience Publishers, Inc., New York, N. Y. (1959).

A theory is presented which states that solid corrosion products cathodically deposited within active cracks in the steel exert a wedging action which develops lateral tensile forces. Combined with the residual and applied stresses present, these forces are sufficient to trigger spontaneous crack propagation. (Also see Reference (245))

(235) A. I. Petrovich, "Metallurgy—Important Factor in Corrosion Science," *Industrial and Engineering Chemistry*, Vol. 51, No. 2, p. 73A (1959).

Earlier approaches to corrosion have bypassed internal workings of metal for consideration of corroding medium and liquid-metal interface. Corrosion science must extend its consideration to phenomena such as dislocations occurring inside metals, particularly in that portion of the metal immediately adjacent to the surface. Direct influence of these phenomena on hydrogen embrittlement and stress corrosion is shown in discussion of dislocation theory and role of hydrogen. The failure of annealed type 304 stainless steel in high pressure hydrogen is mentioned.

(236) F. A. Prange, "Mechanical Properties and Corrosion Resistance of Oil Well Tubing," *Corrosion*, Nat. Assn. Corrosion Engrs., Vol. 15, p. 49t; Discussion by R. L. McGlasson and J. E. Landers, p. 53t (1959).

A resumé of applications of various grades of tubing in sweet and sour condensate wells and sweet and sour oil wells. Corrosion resistance and mechanical properties are considered for 9 per cent nickel steel and 9 per cent chromium steel among others. In discussion, comments are made on stress-corrosion cracking of 9 per cent chromium steel and 9 per cent nickel steel in sweet condensate oil wells with a trace of hydrogen sulfide.

(237) D. K. Priest, "Electrochemical Aspects of Stress-Corrosion," *Journal*, Electrochemical Society, Vol. 106, p. 358 (1959).

From a literature review and the author's work with a J1 alloy, it is concluded that in ductule materials transgranular stress corrosion takes place only under the driving force of a continuous electrochemical action which causes very localized removal of metal by corrosion. The site of metal removal (the crack tip) and the direction of cracking are determined by stress acting to cause localized potential differences through the interruption of film forming mechanism or by intense, localized plastic deformation.

(238) G. E. Rowan, "Stainless Steels to Combat Corrosion," *Canadian Mining and Metallurgical Bulletin*, Vol. 52, p. 255 (1959).

A review article in which stress corrosion of stainless steels is described together with precautions to avoid it. Two cases are cited, caused by chloride-containing magnesia insulation and unrelieved stresses due to fitting or welding.

(239) R. W. Staehle, F. H. Beck, and M. G. Fontana, "Mechanism of Stress-Corrosion of Austenitic Stainless Steels in Chloride Waters," *Corrosion*, Nat. Assn. Corrosion Engrs., Vol. 15, p. 373t (1959).

Stress-corrosion cracking of austenitic stainless steels was studied under various conditions of stress, chloride concentration, complete immersion of specimens, intermittent wetting and drying, and presence of oxygen. Stress-corrosion cracking will occur at stresses as low as 2000 psi at 50 ppm NaCl. A three-dimensional analysis of stress-corrosion cracks was made and a mechanism of cracking proposed. (Also see Reference (**219**).)

(240) H. Suss, "Susceptibility of AISI 410 to Stress-Corrosion Cracking in High Temperature, High Purity Water," KAPL-M-HOS-6 (1959); *Nuclear Science Abstracts* (U. S. Atomic Energy Commission), Vol. 13, No. 13, p. 1591 (1959).

AISI 410 stainless steel tempered at 650 F to hardness of Rockwell hardness C 36 to 42 was being considered as the material for a highly stressed part of a pressure-retaining member in contact with high-purity, high-temperature water. The AISI 410 Steel did not indicate susceptibility to stress-corrosion cracking in hydrogen ammoniated (8.5 to 9.5 pH) or hydrogen-lithium hydroxide waters (11 pH) at 300 F for 6 months exposure. Nickel and chromium plates were also tested for stress-corrosion cracking in the same systems. Results are included.

(241) H. H. Uhlig and R. A. White, "Some Metallurgical Factors Affecting Stress-Corrosion," Preprint by Massachussets Institute of Technology (1959); Submitted to American Society for Metals for publication.

Tests on stress-corrosion cracking of 18-8 stainless steels in boiling 42 per cent $MgCl_2$ (154 C) show that alloys containing 0.015 per cent carbon or 0.01 per cent nitrogen or less do not fail within maximum time of exposure (200 to 260 hr). Commercial 304 alloys, on the other hand, fail within 0.2 to 1.4 hr. Contains tables and references.

(242) H. H. Uhlig, "New Perspectives in the Stress-Corrosion Problem," Physical Metallurgy of Stress-Corrosion Fracture (T. N. Rhodin), Metallurgical Society of AIME, Metallurgical Society Conferences, Vol. 4, Interscience Publishers, Inc., New York, N. Y. (1959).

Examples of various metal cracking. Discusses theories of stress-corosion cracking. Contains tables and figures. Forty references.

(243) "Stress-Corrosion Fracture," Notes from papers presented at a Technical Conference on Physical Metallurgy of Stress-Corrosion Fracture, Am. Inst. Mining, Metallurgical, and Petroleum Engrs., (1959); *Metal Progress*, Vol. 75, No. 6, pp. 143–144, 149A, 150, 152, 154, 156 (1959).

Concise digests of 14 papers.

(244) M. B. Strauss and M. C. Bloom, "The Cracking of Low Carbon Steel During Heating with Aqueous Slurries of Gamma Ferrous Hydroxide," *Journal*, Electrochemical Society. (In preparation.)

(245) A. J. Forty and H. Y. Willis, "Crack Formation in Ductile Crystals and Its Bearing on Stress Corrosion," Physical Metallurgy of Stress Corrosion Fracture. Interscience Publishers Inc., New York, N. Y. (In preparation.)