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MATERIALS FACTORS INFLUENCING THE INITIATION OF NEAR-NEUTRAL pH SCC ON UNDERGROUND PIPELINES

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ABSTRACT

This paper summarizes the results of research, funded by the Canadian Energy Pipeline Association (CEPA), to determine whether the initiation of near-neutral pH stress corrosion cracking (SCC) could be correlated with pipe metallurgical factors. The factors considered included residual stress, surface roughness, chemical composition, cyclic stress-strain behavior, inclusion properties (number, area, and composition), microhardness, and local galvanic behavior. The project focused on pipes installed from the 1950s through 1970s that exhibit near-neutral-pH SCC. Fourteen pipe samples were examined, ranging in diameter from 8 to 42 inches and grades from X52 to X70.

INTRODUCTION

It is now recognized that there are two forms of external SCC on underground pipelines; namely high-pH SCC (also referred to as classical SCC) and near-neutral-pH SCC (also referred to as low-pH SCC). A characteristic of both forms of SCC is the presence of colonies of up to hundreds of longitudinal surface cracks in the body of the pipe that link up to form long shallow flaws. The fracture faces are covered with black magnetite or iron carbonate films. One distinguishing characteristic between the two forms of cracking is the crack path. Near-neutral-pH SCC is transgranular while high-pH SCC is intergranular. There also is generally more corrosion of the crack walls and pipe surface with the near-neutral pH form of cracking than with high-pH SCC.

A number of factors influence the likelihood of initiation of SCC on the external surface of an underground pipeline and the controlling factors may differ for the two forms of cracking. These factors can be broken down into the broad categories of environment, stress, and metallurgy. Specific environments must develop at the pipe surface for stress corrosion cracks to initiate. An intact coating that excludes groundwater from the pipe surface will prevent crack initiation. The relationship between metallurgical factors, such as composition and microstructure of the pipe steel, and initiation of SCC is not well understood, but differences in the SCC susceptibility of different steels have been observed in laboratory tests [1]. Furthermore, field experience suggests that some pipeline steels are more susceptible to SCC than others.

Metallurgy and stress are closely linked in the cracking process. The primary source of stress in operating pipelines is the hoop stress that results from the internal pressure. Residual stresses from fabrication (e.g. welding and bending), surface preparation prior to coating, installation, and mechanical damage can contribute to the total stress at a location on a pipeline. Stress concentrators also are present on pipelines as a result of surface preparation, localized corrosion, and mechanical damage. The likelihood of initiation of SCC at a given location may be affected by all of these stress-related factors.

Cyclic micro plasticity (micro-yielding) also is believed to affect the initiation of both forms of SCC. Micro plastic deformation refers to a very small amount of plastic or permanent strain [2]. Initiation occurs on the scale of the grains of the steel. New surfaces caused by localized micro plastic strain are believed to act as initiation sites.

In summary, there is an overall consensus among researchers concerning the factors that are likely to contribute to initiation of SCC on operating pipelines. However, these factors have not been prioritized with respect to their contribution to the cracking process and the specific metallurgical parameters that control initiation have not been identified.

The objective of the research summarized in this paper was to determine whether there exists a correlation between pipe metallurgical factors and SCC initiation. The project focused on pipes installed from the 1950's through 1970's that exhibit near-neutral-pH SCC. Fourteen pipe joints from four pipeline companies were examined. On these pipes, twenty-four SCC colonies and twenty-eight control areas (with no SCC) were evaluated.

APPROACH

Table 1 summarizes the pipe joints included in the study. Pipes F, G, H, I, J, K, L, and M contained long seam welds and were tape coated. All of the colonies and control areas were near the long seam so it is probable that the coating in these areas was disbonded. On the other pipes, the coating was removed before this project was begun, so it could not be determined whether the coating was disbonded in the control areas. It is safe to assume that the coating was disbonded at the SCC colonies. The following properties were measured in or near the SCC colonies and at the control areas on these joints of pipe; surface roughness, residual stress, chemical composition, cyclic stress strain behavior, grain size, microstructure, microhardness, inclusion size, shape and composition, and local galvanic behavior. Further details of the experimental techniques are summarized below.

Residual Stress and Surface Roughness

The location and size of the colonies were confirmed by means of contrast magnetic particle inspection (CMPI). The largest colonies containing the deepest cracks were chosen for the subsequent analyses. The estimated depths of the cracks in each colony were provided by CEPA from a previous project in which the pipe samples were collected and characterized. Two colony areas were chosen from joints that had more than two distinct colonies, while one colony was chosen from joints with one or two distinct colonies, as shown in Table 1. The control areas were located in regions of the pipe that did not contain SCC colonies and were chosen to be the same distance from the longitudinal welds as the colonies studied.

Before residual stress analyses were performed, the surface roughness values in the colonies and control areas were measured using procedures outlined in ASTM Standard D 4417-93 [3]. For this testing, Press-O-Film tape from Testex was used. The tape is made of a compressible layer of foam between layers of tape. The tape was placed on the pipe in the area next to the area prepared for the strain gage. The tape was then rubbed with a burnishing tool, which compressed the foam into the profile of the surface of the pipe. The maximum peak-to-valley height was then measured by using a spring micrometer. This analysis was performed three times per site and an average surface roughness was obtained.

Residual stress values were measured near the SCC colonies and at the control areas by means of a hole drilling technique. Strain gage rosettes were attached to the pipe and small holes were drilled in the center of the rosettes. For the SCC colonies, the rosettes were placed as close as possible to the colonies without placing the rosette across a crack in the colonies. The presence of the hole allows the material around the hole to relax and this relaxation is measured on the strain gage rosette. The residual stresses were then calculated from these relaxation measurements.

The procedures for performing the residual stress analyses were based on ASTM Standard E 837-94a [4]. Following selection of the location for placing the rosette, the surface was lightly ground with SiC paper and finished to 400 grit. A small triple rosette strain gage was then attached to the pipe in the ground area using an adhesive. The rosette used had three gages arranged around a small circle. The elements were arranged such that Element #2 was oriented 45° from Element #1 and Element #3 was oriented 90° from Element #1. In all of the measurements, Element #1 was oriented in the hoop direction. Measurement leads were then soldered to the gage. The gage was checked for electrical continuity and connected to a set of strain gage reading boxes.

The hole-drilling device was positioned over the strain gage rosette. A small microscope with a positional crosshair was placed in the hole-drilling setup to center the device above the center circle of the strain gage. The base of the drilling device was then cemented to the pipe and allowed to set. Once the cement had set, the microscope was again used to reposition the stage over the exact center of the gage. The microscope was then replaced with a drill. A new drill bit was used for every location to make sure that a clean hole was made for each analysis. A hole was then drilled into the pipe through the center of the strain gage. Drilling was stopped at 0.127, 0.254, 0.508, 0.762, 1.02, 1.27, and 1.52 mm and a reading were taken on each of the three gages of the rosette. From these readings, the average residual stress for the surface layer to each depth was calculated using equations from ASTM Standard E 837-94a (4).

Several additional residual stress measurements were performed to gather information about how residual stress varied with distance from an SCC colony. Sites were selected so that a line of rosettes was arranged either longitudinally or circumferentially from an SCC colony. These areas were then prepared and tested as described above. In total, seventy-two residual stress and surface-roughness measurements were conducted.

Chemical Composition and Tensile Properties

After completing the residual stress and surface roughness measurements, the pipe joints were cut to obtain smaller samples for further analyses. A 61 cm × 61 cm (two × two foot) plate was marked and flame cut out of each pipe centered on the location of the residual stress measurements. On the eight and ten-inch pipes, a 61 cm (two-foot long) section of pipe was cut from the joints. These samples were then further cut down to obtain samples. The cuts were made with a metal cutting band saw and heat input in the samples was minimized.

A small sample was removed from each plate for chemical analysis. Spectroscopic analysis was performed on each SCC and non-SCC area employing ASTM Standard A 751-92 [5]. Analyses were performed for C, S, P, Si, Mn, Ni, Cr, Mo, V, Cu, Nb, Ti, Al, B, Sn, Co, As, Ca, Pb, and Zr.

Three longitudinal bars 6.35 cm × 30.48 cm (2.5 by 12 inches) were cut out of each pipe for tensile testing. ASTM Standard A 370-92 [6] was employed to determine the mechanical properties. Using these methods, the yield stress, ultimate tensile stress (UTS), and elongation were determined. These experiments were performed for the entire pipe instead of for SCC and non-SCC areas because it was impossible to obtain three tensile straps out of each SCC plate close enough to the colony and still consider the area to be removed in the SCC area.

Cyclic Stress Strain Behavior

Cyclic stress-strain tests were performed on transverse smooth tensile specimens of the pipe steels under simulated operating conditions, consisting of high maximum stresses and high R ratio (minimum to maximum load). These conditions produce cyclic creep, which has been speculated to promote SCC initiation and growth.

The pipe samples contained curvature, limiting the length and diameter of the transverse specimens. Cylindrical specimens were machined from the pipe and the specimens had a total length of 25.4 mm (1 inch), a gage length of 6.35 mm, and a gage diameter of 2.54 mm. Specimens for the 8-inch diameter pipe had a gage diameter of 2.03 mm. The surface finish on the specimens was 32 μm RMS, which is the equivalent of a 320-grit finish. Specimen machining removed the original outside diameter surface of the pipe and the diameter of the gage section of the specimens was too small to mount strain gages. Thus, it was necessary to use a clip gage (Interlaken Model 3541-01), mounted to the grips, to measure the strain in the tests.

The experiments were performed in a servo-hydraulic testing machine. Before testing, the maximum load for cycling was determined from the specified minimum yield strength (SMYS) and the measured cross sectional area of the gage section of the specimen. Specimens were tested as a percentage of SMYS because pipelines operate at a given percentage of SMYS not a percentage of the actual yield stress of each pipe joint. One specimen, from each of the fifty-two pipe areas, was tested at 100% of SMYS. For a few pipes, specimens were tested at 80% and 90% of SMYS to generate cyclic stress-strain curves.

The specimens were placed in the grips, with a clip gage attached to the grips, and placed in the test machine. The specimens were loaded to the minimum test load at a ramp rate of 69 kPa (10 pounds) per second. The load was then cycled at a rate of one cycle per minute (0.0167 hertz) with a stress ratio of 0.9. Each specimen was run for 60 cycles, recording the load, displacement, and elapsed time every second.

Grain Size, Microstructure, Microhardness, Inclusion Size, Shape and Composition

A 10.16 cm × 10.16 cm (four × four inch) plate was cut from each large plate for metallographic analysis. This plate was then flatted in a press. A sample, with an area of between 1.27 and 1.9 cm^2, was removed from the plate and mounted in epoxy so that the outer diameter surface was exposed. Standard through-thickness samples were also examined to determine the morphology of the cracks.

The plate samples were ground with successive SiC papers down to 2400 grit and then polished with 0.05 μm alumina oxide on a polishing wheel with all specimen preparation done according to ASTM Standard E 3-80 [7]. Samples were ground until a smooth metal surface was present. The amount of grinding varied between samples since some samples had more corrosion or other features on the surface, but generally less than 0.5 mm was removed.

The samples were examined in a light microscope and two photomicrographs were taken of each sample at 200X. Computer images of these photographs were captured using a scanner. An image analysis program (Scion Image) was used to measure the number of inclusions and the size of each inclusion. These data were recorded for each sample and tabulated on a spreadsheet. From these data, comparisons between SCC and non-SCC areas could be made based on the number of inclusions and the area of these inclusions.

The polished samples were examined in a scanning electron microscope (SEM) and six inclusions per sample were analyzed by means of energy dispersive spectroscopy (EDS). Following SEM examination, microhardness measurements were performed on the samples. A Knoop indentor and a 500-gram load were used to make five measurements at random locations on each sample; the five readings were averaged to obtain the average microhardness.

The samples were then etched with a 4% nital etchant to reveal the grain structure, and photographed. The grain size was found using the comparison procedure outlined in ASTM Standard E 112-88 [8]. The microstructure of each etched samples were also examined in an optical microscope. Through-thickness samples were removed from each crack colony, mounted, polished to 0.05 μm, and etched in 4% nital. The samples were examined and photographed in an optical microscope to determine the crack morphology and the through-thickness microstructure.

Local Galvanic Behavior

The local galvanic behavior was studied in areas with cracking using a scanning reference electrode technique. Plates approximately 30.5 cm × 35.5 cm (12 × 14 inches) were cut out of the pipe bodies in areas of SCC colonies that had not been studied previously. New colonies were selected because the earlier subtasks required that several pieces be cut out from the colony areas, which did not leave a large enough continuous area for this study.

Before each experiment was begun, the plate was placed in a small tub of NS4 electrolyte for twenty-four hours. NS4 is a simulated electrolyte associated with near-neutral-pH SCC on TCPL's system. The scanning reference electrode was setup so that the SCC colony and surrounding areas not containing cracking could be examined. The probe electrode was then moved over the surface and a corrosion potential measurement was taken every 2.54 cm (inch). A 20 cm × 23 cm (8 × 9 inch) area was scanned on each plate and the data were plotted as ISO-potential maps to show cathodic and anodic areas on the scanned areas. The location of the SCC colony was added to each of these plots to determine if the change in potentials were related to the locations of the SCC colonies.

Data Analysis

In situations where trends were evident in the data, a two-sample Student's t-test was performed on the means for two data sets; the values for the SCC areas and the values for the non-SCC areas. This statistical analysis technique is commonly used for small data samples (<30) and assumes that the population of data are normally distributed. The analysis determines whether the two samples come from the same or different populations. If the two samples come from the same population, it can be interpreted to indicate that there is no significant relationship between the parameter (e.g., residual stress) and the presence or absence of SCC. A p-value is determined for the analysis, which is equal to 1 − (level of confidence). For most engineering analyses, a p-value of 0.05, which corresponds to a confidence of 0.95 or 95%, is commonly used to assess whether a parameter is statistically significant.

In the case of the microhardness readings, the pipe-to-pipe variations in the hardness values were larger than the differences between the hardness of the SCC and non-SCC areas. Nevertheless, a simple examination of the data indicated that the microhardness was consistently higher in the SCC areas. Accordingly, a slightly different statistical analysis was performed. In this analysis, a difference in hardness, between the SCC and non-SCC areas, was calculated for each pipe and a 1-sample t-test was performed to determine whether the difference was non-zero.

RESULTS AND DISCUSSION

Residual Stress

Typical curves of residual stress measured at increasing depth are shown in Figure 1. These are the maximum stresses measured for each depth and the orientation of the maximum stress varied as a function of depth and sample. In all of the measurements, the highest principal residual stress was in the hoop direction. The data in Figure 1 show that the residual stresses near the free surface were frequently compressive. With increasing depth, the residual stresses became tensile, and generally increased with increasing depth, up to a plateau value, at a depth of approximately 1.5 mm (15% of the wall thickness).

The plateau residual stress values for each location tested for each pipe joint are given in Figure 2 and a box plot of the data is presented in Figure 3. For the joints where only one SCC colony was tested, the residual stresses in the two control areas were averaged into one value for the comparisons. These data show that the residual stress was almost twice as high near the SCC colonies, as it was in non-SCC areas. The average residual stress for the SCC colonies was 216 MPa (31.3 ksi), with a standard deviation of 104 MPa. The average residual stress for the non-SCC areas was 108 MPa (15.7 ksi), with a standard deviation of 65.6 MPa. The median residual stress was 221 MPa for the SCC colonies and 100 MPa for the non-SCC areas. A two sample t-test was performed on the values of residual stress for SCC and non-SCC areas, resulting in a p value of 0.0002. This value represents a confidence of 99.98% that the SCC and non-SCC data sets are statistically different.

The relationship between residual stress and the presence of the SCC colonies is also evident in the results of residual stress measurements obtained in the vicinity of the colonies. On several pipe samples, a series of measurements was made as a function of distance from the colonies. Typical results, given in Figure 4, show that the residual stress decreased with increasing distance from the colony. These measurements were made circumferentially from the colony, but similar results were obtained for measurements made in the longitudinal direction.

Surface Roughness

The surface-roughness measurements are summarized in Figures 5 and 6. These figures show that the surface-roughness values were slightly higher for areas with SCC colonies. The average peak-to-valley reading was 93.2 μm for SCC areas and 86.4 μm for non-SCC areas. The median for both SCC and non-SCC areas was 88.9 μm. The standard deviation was 19.8 μm for the SCC areas and 14.9 μm for non-SCC areas. A two-sample t-test, performed on the SCC and non-SCC values, gave a p-value of 0.13. A one-sample t-test, performed by subtracting the non-SCC value from the SCC value, gave a p-value of 0.12. These p-values correspond to confidence levels of 87 to 88%, which are below standard confidence level of 95%; but, nevertheless, suggest a possible correlation.

Chemical Composition and Tensile Properties

Chemical analyses were performed on the fifty-two samples removed from the pipe joints. The chemical compositions did not vary much for samples taken at different locations of the same pipe joints. Although a rigorous statistical analysis was not performed, no trends were evident in the pipe composition data between the SCC locations and the locations remote from the SCC colonies. Tables 2 shows the average chemical compositions of each of the pipes, grouped by pipe grade, with the chemical specifications for each grade of pipe. These data show that Pipe L had more carbon than allowed by present API 5L specifications, but all of the other X52 and X60 samples met the API requirements. Of the X65 samples, both G and H had higher manganese levels than allowed in the specification. Pipe N had a higher level of manganese than allowed for X70 line pipe steel in the specification.

The results of the tensile testing are given in Tables 3. These results are an average of the three tests performed on samples from each pipe and are listed with the API 5L minimum specifications with each grade. Samples from Pipe K had a lower than specified yield stress, but all other X52, X60, and X70 pipe samples met specifications. Samples from Pipe I had a lower than specified yield stress, but all other X65 pipe samples met specifications.

Grain Size, Microstructure, Microhardness, Inclusion Size, Shape and Composition

Five microhardness measurements were performed on each of the 52 study areas. These measurements were averaged for each area and the results are plotted in Figure 7. The figure shows that the microhardness was slightly higher in SCC areas than non-SCC areas for 12 of the 14 pipes. The average microhardness for SCC areas was 210 Knoop Hardness (KHN), compared to 202 KHN for non-SCC areas. The median hardness was 214 KHN for SCC areas and 203 KHN for non-SCC areas. A two-sample t-test on these data sets had a p-value of 0.36 suggesting that there is no statistical difference between the data sets. The two data sets were reduced to one set by subtracting, for each pipe, the non-SCC microhardness values from the SCC microhardness values. A one-sample t-test was performed on the data, resulting in a p-value of 0.063, which is almost significant at the 95% level, showing a correlation likely exists. A different method of statistical evaluation were required for microhardness because the difference in hardness between pipes (the high standard deviation) is greater than the hardness difference between the SCC and non-SCC samples on a given pipe.

No statistically significant correlation was found between the occurrence of SCC on the pipes and the other factors evaluated in the study; cyclic stress-strain behavior, inclusion properties (number, area, and composition), and local galvanic behavior. This does not prove that these factors are unimportant in SCC initiation behavior. All of the joints of pipe used in this study were "susceptible joints," based on the fact that they all contained colonies of stress corrosion cracks. Thus, some of these factors, such as cyclic stress-strain behavior, or inclusion composition, may have been in the susceptible regime for all of the test samples.

CONCLUSIONS

The results of this study indicate a strong correlation between residual stress and the presence of near-neutral pH SCC colonies. The mean residual tensile stress near the SCC colonies was about twice as high as in the control areas (216 MPa versus 108 MPa) and the difference was highly statistically significant at a 99.98% confidence level.

The microhardness within the SCC colonies was also higher than that measured in the control areas, with a mean difference of 7.46 KHN, and the difference was statistically significant at a confidence level of 93.7%.

There was a possible difference in the surface roughness between the SCC and non SCC areas, with a confidence level of 87 to 88%. The average roughness for the SCC areas was 93 μm versus 86 μm for the non-SCC areas.

No statistically significant correlation was found between the occurrence of SCC on the pipes and the other factors evaluated in the study; chemical composition, cyclic stress-strain behavior, inclusion properties (number, area, and composition), and local galvanic behavior. All of the joints of pipe used in this study were "susceptible joints" and thus, some of these other factors may affect cracking behavior, but may have been in the susceptible regime for all of the test samples.

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Table 1. Background data on pipes examined for this project.

Pipe No.	CCT ID No.	No. of SCC Colonies	No. of SCC Colonies Studied	No. of Non-SCC Areas Studied	Length (m)	Diameter (mm)	Diameter (in)	Wall Thickness (mm)	Wall Thickness (in)
1	A	1	1	2	6.10	254	10	5.1	0.2
2	B	2	1	2	6.10	254	10	5.1	0.2
3	C	2	1	2	6.09	254	10	5.1	0.2
4	D	26	2	2	18.71	219	8.625	3.8	0.15
5	F	4	2	2	4.60	1067	42	10.7	0.42
6	G	72	2	2	12.21	1067	42	10.7	0.42
7	H	23	2	2	5.50	1067	42	10.7	0.42
8	I	65	2	2	9.79	914	36	10.7	0.42
9	J	40	2	2	12.26	914	36	9.53	0.375
10	K	25	2	2	12.17	508	20	6.35	0.25
11	L	82	2	2	15.49	508	20	6.35	0.25
12	M	5	2	2	15.23	508	20	6.35	0.25
13	N	7	1	2	12.06	1067	42	16.0	0.63
14	O	–	2	2		457	18	6.35	0.25

Table 2. Average chemical compositions for the pipe samples; balance Fe. The current API specifications are also listed.

Pipe Sample	Grade	C	Mn	P	S	Si	Cu	Sn	Ni	Cr	Mo	Al	V	Nb	Zr	Ti	B	Ca	Co
A	X52	0.23	0.907	0.009	0.0197	0.0083	0.0203	0.005	0.014	0.025	0.006	0.012	0.002	0.0253	0.000	0.002	0.0002	0.0007	0.005
B	X52	0.21	0.8	0.004	0.0143	0.0063	0.016	0.003	0.011	0.022	0.004	0.0167	0.002	0.0253	0.000	0.002	0.0002	0.00037	0.004
C	X52	0.21	0.783	0.005	0.0163	0.008	0.0227	0.003	0.017	0.014	0.005	0.0117	0.0017	0.024	0.000	0.002	0.0002	0.00023	0.004
D	X52	0.27	0.978	0.006	0.0155	0.0145	0.0488	0.005	0.019	0.0205	0.005	0.0315	0.0023	0.0033	0.000	0.002	0.0002	0.0001	0.004
K	X52	0.25	0.963	0.0123	0.0165	0.0228	0.0328	0.0035	0.015	0.029	0.005	0.0043	0.002	0.0038	0.000	0.002	0.0002	7.5E-05	0.00625
L	X52	0.29	1.175	0.0123	0.0198	0.0055	0.0513	0.0148	0.016	0.0313	0.0055	0.0338	0.003	0.0038	0.000	0.002	0.0003	0.00023	0.006
M	X52	0.25	1.11	0.0108	0.0205	0.005	0.0995	0.0095	0.0318	0.0305	0.007	0.0145	0.003	0.004	0.000	0.002	0.0003	0.00035	0.006
API 5L X 52	-	0.28*	1.25*	0.030*	0.030*	-	-	-	-	-	-	-	-	-	-	-	-	-	-
O	X60	0.16	1.133	0.005	0.0193	0.0625	0.311	0.0258	0.4753	0.3973	0.0293	0.02	0.075	0.0048	0.001	0.0023	0.0003	0.00025	0.012
API 5L X 60	-	0.26*	1.35*	0.030*	0.030*	-	-	-	-	-	-	-	-	-	-	-	-	-	-
F	X65	0.08	1.305	0.0085	0.003	0.31	0.1685	0.002	0.1315	0.014	0.004	0.034	0.044	0.0238	0.0003	0.0035	0.0003	0.00453	0.007
G	X65	0.07	1.548	0.019	0.006	0.25	0.01	0.003	0.013	0.023	0.004	0.0308	0.0463	0.036	0.0005	0.004	0.0004	0.00158	0.004
H	X65	0.1	1.488	0.0163	0.005	0.32	0.0073	0.002	0.0083	0.014	0.004	0.0258	0.0618	0.0283	0.0003	0.003	0.0005	0.00075	0.004
I	X65	0.13	1.39	0.0105	0.0128	0.3225	0.0273	0.004	0.022	0.036	0.007	0.0373	0.0058	0.0293	0.048	0.003	0.0003	0.00013	0.005
J	X65	0.14	1.38	0.007	0.004	0.34	0.038	0.013	0.039	0.049	0.009	0.034	0.005	0.031	0.055	0.003	0.0002	0.0001	0.008
API 5L X 65	-	0.26*	1.40*	0.030*	0.030*	-	-	-	-	-	-	-	-	-	-	-	-	-	-
N	X70	0.06	1.73	0.0123	0.0073	0.27	0.0277	0.004	0.0137	0.205	0.1687	0.0353	0.051	0.0437	0.001	0.003	0.0003	0.00203	0.004
API 5L X 70	-	0.23*	1.60*	0.030*	0.030*	-	-	-	-	-	-	-	-	-	-	-	-	-	-

* *Maximum*

Table 3. Average tensile properties for the pipe samples. The current API specifications are also listed.

Pipe (CCT ID)	Average Yield Strength (MPa)	Average Yield Strength Ksi	Average Ultimate Strength (MPa)	Average Ultimate Strength Ksi	Average Elongation (%)
A	426.7	61.9	515.	74.8	30
B	393.6	57.1	495.7	71.9	37
C	383.3	55.6	467.4	67.8	38
D	430.9	62.5	575.0	83.4	33
K	336.4	48.8	500.5	72.6	34
L	421.2	61.1	583.2	84.6	33
M	381.2	55.3	529.5	76.8	37
API 5L X 52	358.5 *	52.0 *	455.0 *	66.0 *	26 *
O	459.2	66.6	592.9	86.0	34
API 5L X 60	413.6 *	60.0 *	517.1 *	75.0 *	23 *
F	488.8	70.9	566.0	82.1	35
G	464.7	67.4	541.9	78.6	38
H	474.3	68.8	567.4	82.3	37
I	426.0	61.8	561.9	81.5	40
J	444.7	64.5	588.7	85.4	40
API 5L X 65	448.1 *	65.0 *	530.8 *	77.0 *	23 *
N	517.1	75.0	641.8	93.1	37
API 5L X 70	482.6 *	70.0 *	565.3 *	82.0 *	21 *

** Minimum*

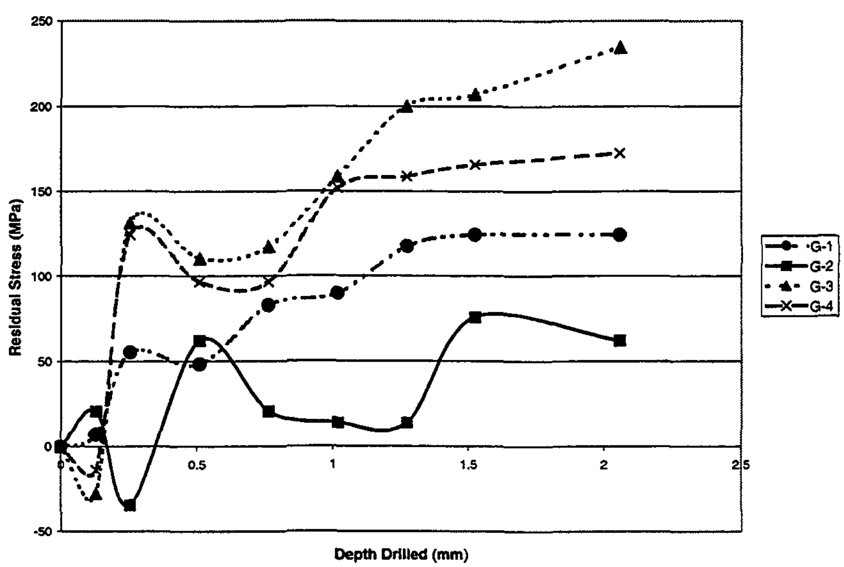

Figure 1. Residual stress as a function of depth for SCC areas (G-3 and G-4) and non-SCC areas (G-1 and G-2) on pipe G.

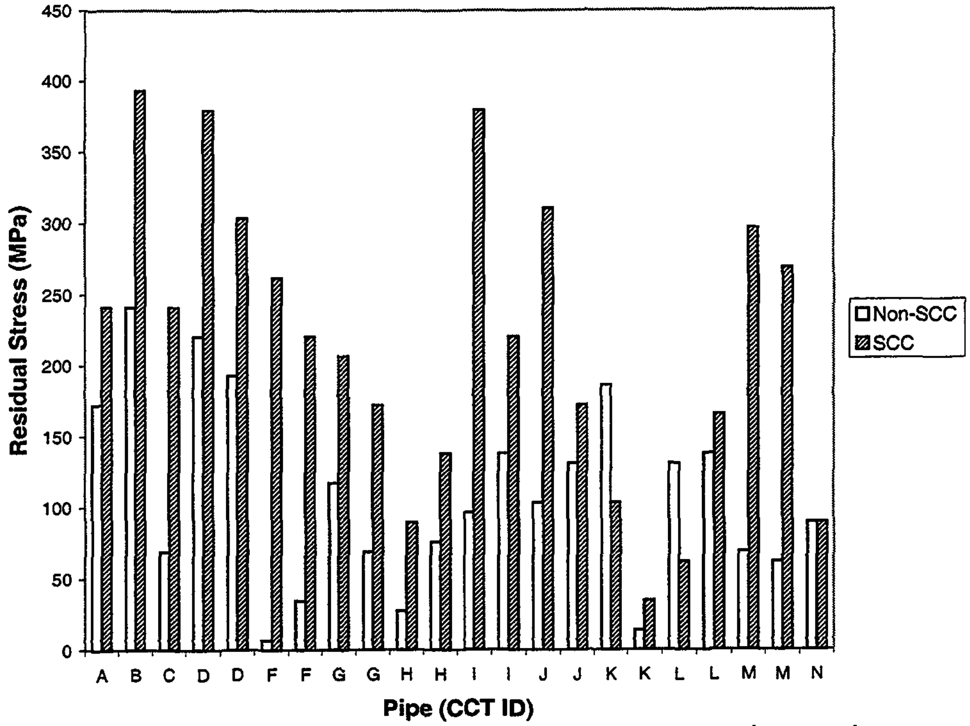

Figure 2. Residual stresses for SCC and non-SCC areas on pipe samples.

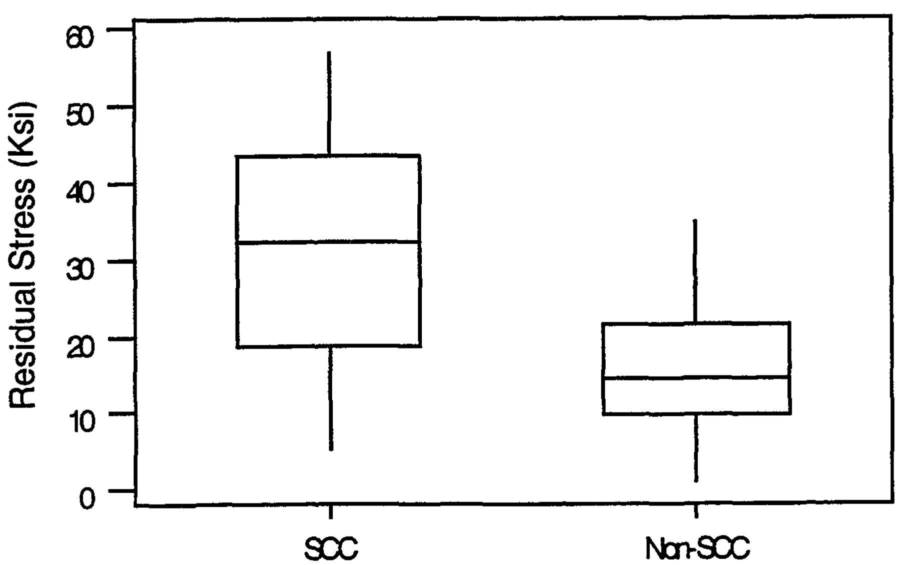

Figure 3. Box plot of the residual stresses for SCC and non-SCC areas.

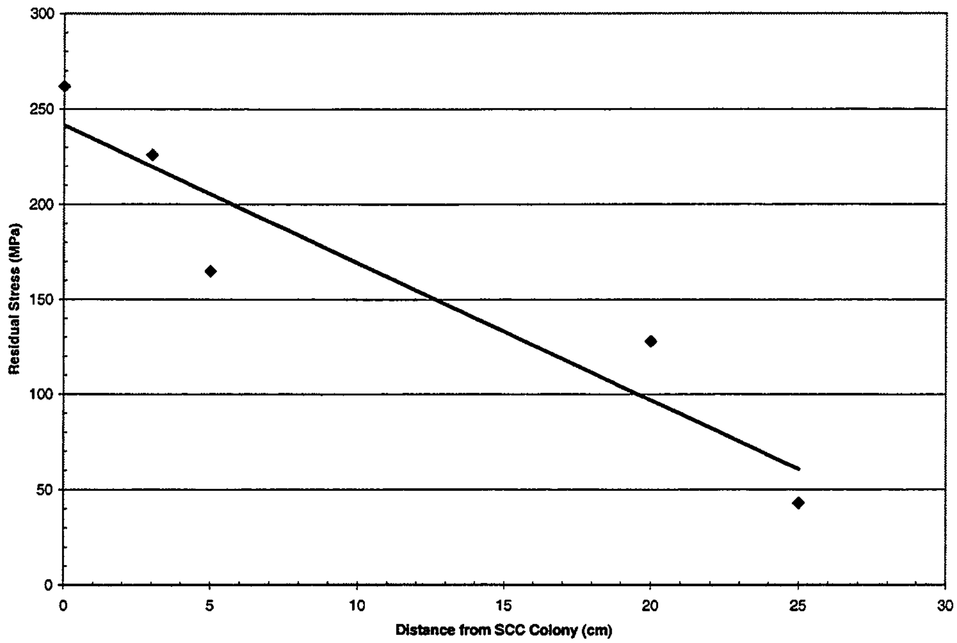

Figure 4. **Residual stress, as a function of distance, (in the circumferential direction) from SCC colony in pipe sample I.**

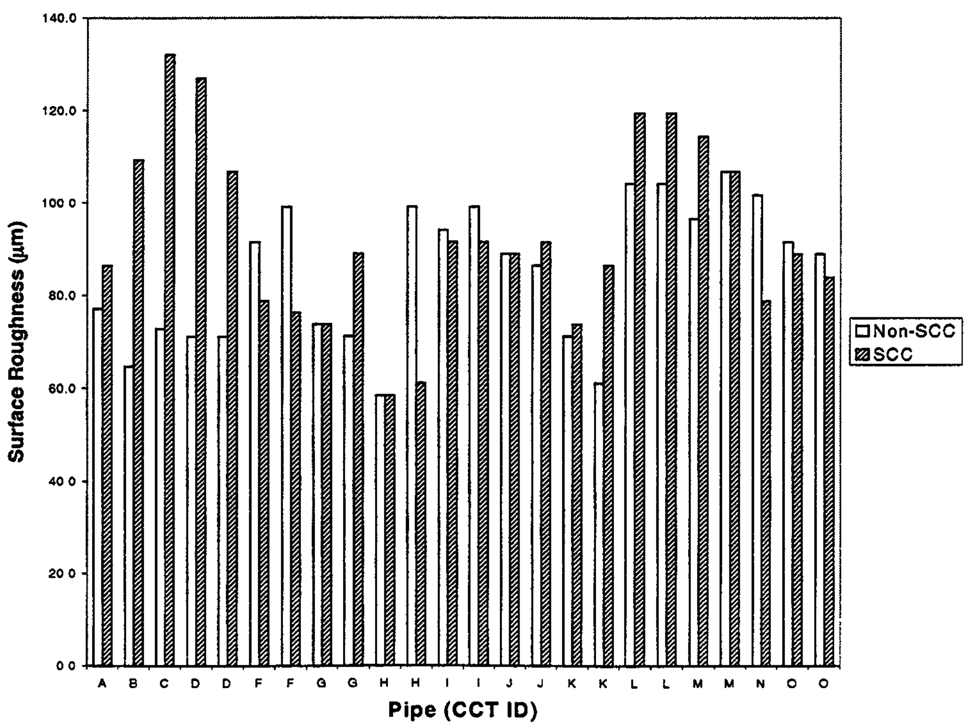

Figure 5. **Results of surface-roughness measurements in SCC and non-SCC areas for pipe samples.**

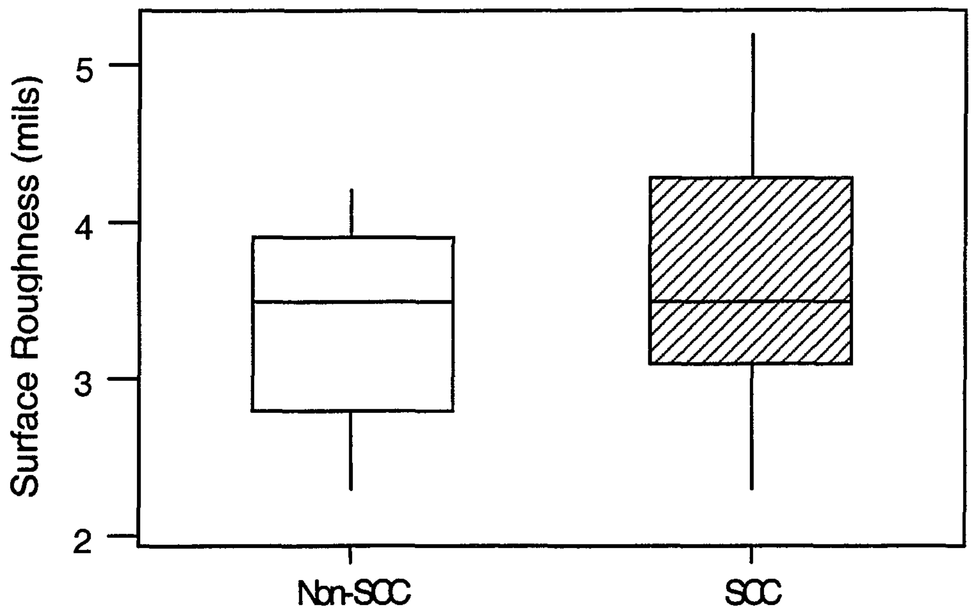

Figure 6. Box plot of the measured surface roughness values or SCC and non-SCC areas.

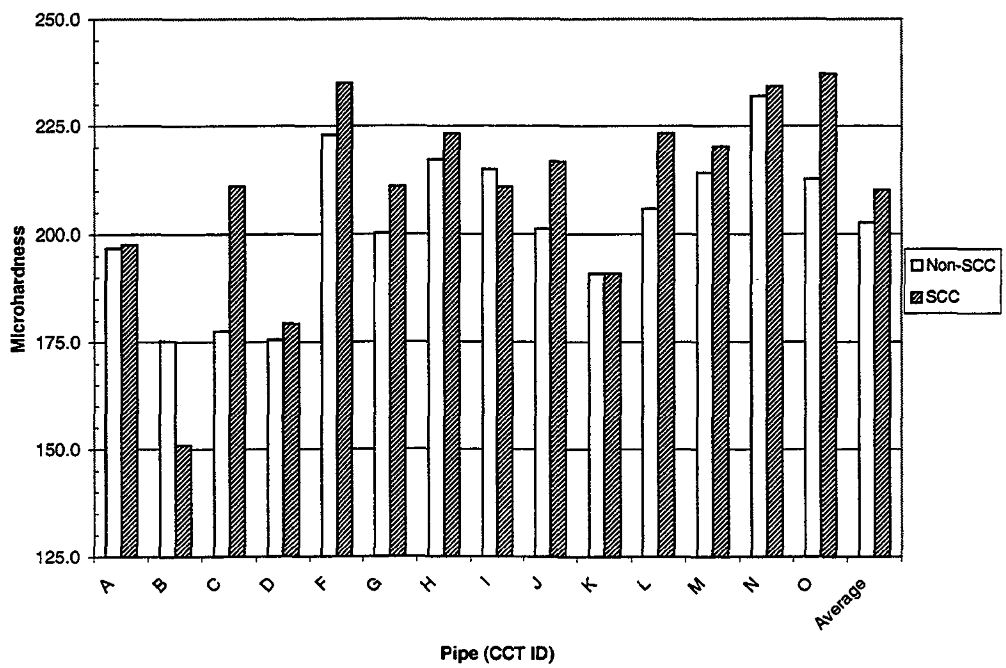

Figure 7. Average microhardness values for SCC and non-SCC areas from pipe samples.