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DEFECT DISTRIBUTIONS IN WELD-DEPOSITED CLADDING

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DEFECT DISTRIBUTIONS IN WELD-DEPOSITED CLADDING

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ABSTRACT

Defect distributions in stainless steel and nickel-chromium alloy weld-deposited cladding over a low alloy steel base were characterized by destructive evaluation (DE). An evaluation of the observed defects was conducted to characterize the defects by type or classification. Size distributions of cladding defect types were developed from the information obtained. This paper presents the results of the cladding evaluation.

BACKGROUND

In pressure vessel and piping applications, the function of the cladding is to protect the underlying vessel or piping from corrosion. In the case of steel pressure vessels, laboratory experiments have shown that fatigue crack propagation (FCP) of typical pressure vessel (PV) steels in aqueous environments can, under some conditions, be accelerated to much higher rates than expected in air under the same loading conditions. Such a phenomenon has been termed environmentally-assisted cracking (EAC) and numerous papers have been written on this subject. Given the possibility of EAC, the potential penetration of the cladding could expose the underlying steel vessel to the aqueous environment. Cracking of the cladding is one possible manner that might bring about EAC.

The possibility of cracking in cladding is real and has been reported in various cases over the last 30 years or so. Wimunc (1966) reviewed four cases where cladding failures have been detected in pressure vessels. In one case, that of the Elk River reactor vessel, cracks were found in weld-deposited cladding during the 1961 prestartup inspection. Although these

initial cracks were repaired by grinding and redepositing new cladding material over the ground out areas, additional cracks were again found in the cladding after one full-power year of operation. Cracking was also reported in stitch bonded cladding by Wimunc in the three other cases. Kondo et al., (1971) also reported cracking in the weld-deposited cladding of a Japanese boiling water reactor. Some of the reported cracks were observed to have extended through the cladding and into the steel pressure vessel. In 1990, another case of cracking was discovered during refueling at Quad Cities Unit 2. Numerous cracks were found in the reactor head cladding and the heat-affected zone in the base metal. Both surface and sub-surface cracks of significant size were found. Based on these findings, an information notice was subsequently issued by the US Nuclear Regulatory Commission (NRC) to alert all its licensees of a potential problem related to cracking of cladding and its heat-affected zone in the base metal of a reactor vessel head. The few examples cited here indicate a continual need to understand the factors that can contribute to such occurrences of cracking.

One possible means of cracking is from crack initiation of preexisting cladding defects. The existence of inherent defects within the cladding is real. For example, Pennell (1996) reported a series of tests conducted by W. J. McAfee and B. R. Bass to evaluate the effect of cladding on the fracture behavior of PV steels. Numerous defects were observed in the cladding of test specimens machined from a clad assembly. Defects of various sizes and shapes were discovered in the clad layer, the heat-affected zone (HAZ), and the structural weld being tested. Defects in the form of pores, voids, and inclusions were found; porosity was found at all levels

through the clad layer. Although defect depths were not determined, some defects were found to be of sufficient size such that the specimens were judged to be unfit for testing.

Since the cracking of cladding remains a concern, and since inherent defects exist in weld-deposited cladding and can serve as crack initiation sites¹, it is therefore of relevant interest to examine the nature of these cladding defects and characterize their size distributions within the cladding. Such information may allow for an assessment of the potential for failure originating from defects that are intrinsic to and common in weld-deposited cladding. This paper attempts to characterize the defect population present within typical weld-deposited cladding. The results of metallographic evaluation performed on two types of weld-deposited cladding are presented.

EXPERIMENTAL PROCEDURES

Defect distributions in Type 309/Type 308 stainless steel (UNS S30980/UNS S30880) cladding and nickel-chromium alloy EN82H (UNS N06082) cladding weld-deposited over a low alloy steel base were characterized in this study. Application of the stainless steel cladding was done using a suitable manual shielded metal arc (SMA) weld process. This process of weld deposition is very versatile in that it is portable and can accommodate areas where other processes have limited access. However, the SMA process is also associated with an increased likelihood of process-related defects of various configurations compared to other weld deposition techniques.

For EN82H cladding, a gas-tungsten arc hot wire (GTA-HW) method was used for weld deposition. Although the deposition rate is slower, the GTA-HW technique is believed to be one of the best weld

deposition methods available, capable of producing a cleaner, higher quality cladding. Thus, the two weld deposition techniques used probably represent the two extremes in terms of expected product quality.

Several sample regions of each clad assembly were selected for DE after nondestructive evaluations (NDE) were completed using ultrasonic and radiographic inspection techniques. Specimens were carefully sectioned, then mounted and polished using standard practice for metallography.

DE was performed by incremental grinding operations on the selected specimens. The methods used to examine each of the two types of cladding were very similar. Due to the labor intensive effort required in this study, the scope of the DE work was limited to detecting defects greater than about 0.15 mm (approx. 0.005 in.). That is, defects smaller than this approximate size did not receive any attention and thus were not characterized or tallied.

In general, grinding was performed at increments of about 0.5 mm (0.020 in.) when defects greater than 0.15 mm (approx. 0.005 in.) were found, and about 1.3 mm (0.05 in.) otherwise. Thus, it is clearly possible that some defects might have been overlooked because of the grinding increments chosen.

Electrolytic etching was done for each specimen in order to better characterize the defects found. A chromic electrolytic etchant was initially used for the EN82H cladding, whereas an oxalic acid electrolytic etchant was used for the stainless steel cladding. However, defects generally showed up much better in the as-polished condition, and defect detection was based on optical metallographic inspection of the as-polished specimen surface.

RESULTS AND DISCUSSION

Unless otherwise noted, all defect sizes presented in this paper refer to the maximum observed dimension of the defect in the through clad direction.

¹ It is interesting to note that while defect stringers can also serve as potential link-up paths to material discontinuities such as other defects or cracks, James and Mills (1980) showed that such a condition has no effect on the fatigue crack propagation (FCP) behavior of Alloy 718 weldments (a nickel-base alloy, UNS N07718) produced by a gas-tungsten arc (GTA) method.

Stainless Steel Cladding

The types of defects observed in the stainless steel clad specimens were grouped into three categories based on the following postulated causes:

- (a) Defect Type S1: Clad material defects such as pores or microcracks occurring within an individual weld bead. This defect type is considered to be uniformly distributed throughout the cladding volume.
- (b) Defect Type S2: Longitudinal type defects occurring between weld passes, possibly caused by slag or debris not fully dissolving in the weld pool. The number of defects of this type is assumed to be proportional to the total length of weld pass in a clad volume.
- (c) Defect Type S3: Transverse defects occurring at weld starts caused by inadequate bonding of the start of a weld pass. The number of defects of this type is assumed to be proportional to the total number of weld starts in a clad volume.

During DE, defect sizes less than about 0.5 mm (0.020 in.) were not considered in the derivation of the defect distribution model. Since the volume of material being examined is small, the cladding was initially fabricated without grinding the weld stops in order to maximize the likelihood of sampling defects associated with weld starts and stops. This might be justified since the manual SMA method used in depositing the cladding is typically performed under less controlled circumstances and the occurrence of inadequate grinding at weld stops might not be that uncommon. Examples of each type of defects are shown in Figures 1 to 3.

The observed defect sizes for each defect type are given in Tables 1 to 3. Distributions are given in terms of the observed cumulative numbers less than a given defect size and a normalized cumulative number.

Type S1 defects were normalized based on an examined clad volume of 9.5 cm³ (0.58 in³). Type S2 defects were normalized based on a calculated weld pass length of 2188.7 cm (861.7 in.). Type S3 defects were normalized based on approximately 73 weld starts.

It is observed that defect sizes tend to be exponentially distributed; the defect size distribution model used in this study was assumed to be of the form:

$$n(<x) = n_0(1 - e^{-b(x-c)}) \quad (1)$$

where

x = defect size in the through clad direction,
 $n(<x)$ = total number of defects less than size x ,
 n_0 , b , and c = constants derived from DE.

All DE results from Tables 1 to 3 were also grouped together and normalized based on the volume of material examined. The size distributions for the three defect types and also for all DE results were developed using the equation (1) model. The exponentially fitted constants for each distribution model are provided in Table 4.

The defect size distribution can be expressed in terms of the total number of defects greater than or equal to x , $n(\geq x)$, as follows:

$$n(\geq x) = n_0 - n(<x) = n_0 e^{-b(x-c)} \quad (2)$$

It is more useful to normalize all the defect distributions to the same units for calculation purposes. Using 279.4 mm (11 in.) of weld pass per rod, one start per rod and a weld rod diameter of 4.76 mm (0.188 in.), appropriate relationships between pass length and starts per volume of weld can be established.

Using the fitted constants of Table 4, Equation (2) can then be expressed in terms of clad volume for each respective defect type as follows:

$$n_{S1}(\geq x) = 3.232 (e^{-4.452(x-0.515)}) V_{\text{clad}} \quad (3)$$

$$n_{S2}(\geq x) = 0.024 (e^{-0.956(x-0.413)}) V_{\text{clad}} \quad (4)$$

$$n_{S3}(\geq x) = 0.040 (e^{-0.577(x-0.457)}) V_{\text{clad}} \quad (5)$$

where n_{Si} represents the total number of Type Si defects greater than or equal to size x (millimeters) in a clad volume, V_{clad} (cm³).

The number and size distributions for each defect type are shown in Figure 4 using equations (3), (4), and (5) assuming a clad volume of 28317 cm^3 (1 ft^3).

EN82H Cladding

The manner in which the defects were grouped or classified differed from that of the stainless steel cladding. However, the method used to develop defect size distributions was the same.

The types of defects observed in the EN82H cladding were also separated into three categories:

- (a) Defect Type E1: Pore-like defect having an associated volume, generally round, and possessing no notable sharp projections that might render a high stress concentration.
- (b) Defect Type E2: Crevice-like defect having an associated volume, not necessarily spherical in shape, and having one or more sharp projections that can act as stress risers. A crevice-like defect can also contain inclusion materials within its cavity.
- (c) Defect Type E3: Tight defect having no notable volume associated with it and most resembling a fatigue crack.

A total of 8 defects was uncovered during DE of about 7 cm^3 (0.425 in^3) of the EN82H cladding. Although the total number of defects observed was small, the total volume of material examined was also small. Thus, on a per volume basis, assuming the volume of cladding examined is representative of bulk cladding volumes, the defect density observed can be taken to be significant.

Of the 8 defects found, 4 were classified as tight defects, while 3 were crevice-like. A number of pore-like indications were observed during the DE process, but only one was within the size limit set for this study. Some small pore-like indications seemed to be correlatable to small pockets of matrix material adjacent to the dendritic structure as seen in the subsequent etched microstructure. However, no effort was made to characterize this observation. The results of the defects found are summarized in Table 5.

Selected samples of each type of defect observed in this evaluation are shown in Figures 5 and 6. All tight cracks found in the cladding were located roughly at an area adjacent to the boundary between clad layers in the final layer of cladding. All crevice-like defects were found at the cladding/base metal interface. None of the tight defects found were oriented in the through clad direction. Examination of the microstructure suggests that the tight defects appeared to be preferentially located in regions lacking in long dendritic structures, and are generally oriented perpendicular to the columnar dendrites within the microstructure.

Because of the small number of defects found, developing defect size distributions based on defect types was not feasible. Therefore, two defect size distributions were developed based on all defects found: a defect size distribution representing the observed maximum defect size in the through clad direction, and a defect size distribution representing the maximum overall size dimension. The maximum overall size is obtained by vectorial summation of the maximum observed dimensions along the Cartesian axes.

To obtain the defect size distributions, the total collected results were rearranged in Table 5 to show the cumulative number of defects found per unit volume of cladding evaluated. Using the extrapolated data of Table 5, the desired defect size distributions for the EN82H cladding were obtained by fitting the data to the exponential model of Equation (1). The fitted model constants are summarized in Table 6.

Consistent with the derivation done for the stainless steel cladding, the distributions are also rendered in the form of Equation (2). Expressing the resulting defect size distributions in terms of clad volume yields Equation 6 representing the size distribution for defect sizes in the through clad direction, and Equation 7 representing the size distribution for the maximum overall defect size:

$$n_{\text{depth}}(\geq x) = 1.291 (e^{-6.287(x+0.045)})V_{\text{clad}} \quad (6)$$

$$n_{\text{size}}(\geq x) = 1.122 (e^{-1.886(x-0.426)})V_{\text{clad}} \quad (7)$$

where x is expressed in millimeters and the clad volume, V_{clad} , in cm^3 .

Since the procedures used in the DE of both the stainless steel and EN82H cladding were very similar, the through clad size distributions for all defect types observed for both types of cladding are plotted together in Figure 7. Also plotted in Figure 7 is the maximum overall defect size distribution for the EN82H cladding. Note that the two through clad size distributions for the two claddings in Figure 7 cannot be compared directly since the collected databases did not overlap; that is, defect sizes less than about 0.5 mm (0.020 in.) were excluded from the development of the size distribution model for the stainless steel cladding. However, examination of the maximum overall defect size for the EN82H cladding shown in Figure 7 clearly indicates that the stainless steel cladding manufactured using the manual SMA technique possessed many more defects of significant sizes than the EN82H cladding fabricated using the GTA-HW technique. Thus, the defect distributions shown in Figure 7 are relatively consistent with the expected quality of cladding based on knowledge of the welding techniques employed.

It is noted here that although the largest defect, a crevice-like defect (a lack of fusion / inclusion defect) with a maximum observed size on the order of 7.4 mm (0.29 in.), was found in the EN82H cladding, it is not known whether any similar defects of comparable or greater dimension existed in the stainless steel cladding since only defect sizes in the through clad directions were acquired.

SUMMARY

Destructive evaluation has been conducted on stainless steel cladding fabricated using the manual SMA technique and nickel-chromium alloy EN82H cladding fabricated using the GTA-HW technique. The objectives of this work were to demonstrate that defects exist in weld-deposited cladding and to characterize the observed defect types and size distributions. The result of this evaluation yielded the following observations:

- A number of defects were found in the limited volumes of both types of cladding examined.
- Defects observed within the weld deposited stainless steel cladding can be categorized into 3 postulated types: defects uniformly distributed

within weld beads, defects located longitudinally between weld passes due to undissolved slag or debris, and defects located transversely between weld passes due to inadequate bonding at the start of weld passes.

- Defects found within the weld deposited nickel-chromium alloy EN82H cladding can also be separated into 3 observed types: pore-like defects possessing no notable sharp projections, crevice-like defects having an associated volume and one or more sharp projections that can act as stress risers, and tight defects having no notable volume and most resembling fatigue cracks.
- Defect size distributions for both types of cladding can be characterized using an exponential model.
- Evaluation of the GTA-HW EN82H cladding showed fewer overall defects of significant size than the SMA stainless steel cladding.
- The defect size distributions observed between the two types of cladding were consistent with the expected quality of the cladding based on knowledge of the welding techniques employed.

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Table 1. SMA Stainless Steel Cladding: Type S1 Defect Results Observed from DE

Type S1 Defect: Maximum Through Clad Size		
Defect Size, x millimeter (inch)	Cumulative Size < x number/9.5 cm ³ or number/0.58 in ³	Normalized Cumulative Size < x number/cm ³ (number/in ³)
0.508 (0.020)	1	0.105 (1.7)
0.533 (0.021)	2	0.210 (3.4)
0.559 (0.022)	4	0.421 (6.9)
0.584 (0.023)	5	0.526 (8.6)
0.610 (0.024)	11	1.157 (19.0)
0.635 (0.025)	14	1.473 (24.1)
0.660 (0.026)	16	1.684 (27.6)
0.686 (0.027)	17	1.789 (29.3)
0.711 (0.028)	19	1.999 (32.8)
0.762 (0.030)	20	2.104 (34.5)
0.787 (0.031)	21	2.210 (36.2)
0.889 (0.035)	24	2.525 (41.4)
0.965 (0.038)	26	2.736 (44.8)
1.016 (0.040)	28	2.946 (48.3)
1.067 (0.042)	29	3.051 (50.0)
1.575 (0.062)	30	3.157 (51.7)

Table 2. SMA Stainless Steel Cladding: Type S2 Defect Results Observed from DE

Type S2 Defect: Maximum Through Clad Size		
Defect Size, x millimeter (inch)	Cumulative Size < x number/2188.7 cm ³ or number/861.7 in ³	Normalized Cumulative Size < x number/cm ³ (number/in ³)
0.559 (0.022)	1	0.000457 (0.00116)
0.635 (0.025)	2	0.000914 (0.00232)
0.813 (0.032)	3	0.001371 (0.00348)
1.041 (0.041)	4	0.001828 (0.00464)
1.499 (0.059)	6	0.002741 (0.00696)

Table 3. SMA Stainless Steel Cladding: Type S3 Defect Results Observed from DE

Type S3 Defect: Maximum Through Clad Size		
Defect Size, x millimeter (inch)	Cumulative Size < x number/73.4 starts	Normalized Cumulative Size < x number/start
0.762 (0.030)	2	0.0272
0.914 (0.036)	4	0.0545
1.422 (0.056)	6	0.0817
1.803 (0.071)	8	0.1090
2.413 (0.095)	10	0.1362

Table 4. SMA Stainless Steel Cladding Defect Model Constants

Model: $n(<x) = n_0(1 - e^{-b(x-c)})$				
Parameter	All DE Data	Type S1 Defect	Type S2 Defect	Type S3 Defect
n_0	4.633 (75.912)	3.232 (52.883)	0.004 (0.011)	0.201 (0.201)
b	3.114 (79.139)	4.452 (114.944)	0.956 (24.151)	0.577 (14.622)
c	0.511 (0.020)	0.515 (0.020)	0.413 (0.016)	0.457 (0.018)
Model Units	defects/cm ³ (defects/in ³)	defects/cm ³ (defects/in ³)	defects/cm (defects/in)	defects/start

Table 5. GTA-HW Nickel-Chromium Alloy EN82H Cladding: Defect Results Observed from DE

All Defect Types: Maximum Through Clad Size		
Defect Size, x millimeter (inch)	Cumulative Size < x number/7 cm ³ or number/0.425 in ³	Normalized Cumulative Size < x number/cm ³ (number/in ³)
0.025 (0.001)	3	0.431 (7.059)
0.038 (0.002)	4	0.574 (9.412)
0.107 (0.004)	5	0.718 (11.765)
0.127 (0.005)	6	0.862 (14.118)
0.168 (0.007)	7	1.005 (16.471)
All Defect Types: Maximum Overall Size		
Defect Size, x millimeter (inch)	Cumulative Size < x number/7 cm ³ or number/0.425 in ³	Normalized Cumulative Size < x number/cm ³ (number/in ³)
0.539 (0.021)	1	0.144 (2.353)
0.621 (0.024)	2	0.287 (4.706)
0.659 (0.026)	4	0.574 (9.412)
0.983 (0.039)	5	0.718 (11.765)
1.318 (0.052)	6	0.862 (14.118)
1.671 (0.066)	7	1.005 (16.471)
7.393 (0.291)	8	1.149 (18.824)

Table 6. GTA-HW Nickel-Chromium Alloy EN82H Cladding Defect Model Constants

Model: $n(<x) = n_0(1 - e^{-b(x-c)})$		
Parameter	Maximum Through Clad Size	Maximum Overall Size
n_0	1.291 (20.652)	1.122 (18.376)
b	6.287 (176.175)	1.886 (47.350)
c	-0.045 (-0.001)	0.426 (0.017)
Model Units	defects/cm ³ (defects/in ³)	defects/cm ³ (defects/in ³)

(a)

(b)

Figure 1. (a) SMA deposited stainless steel cladding showing Type S1 (within weld bead) defects at 5X. (b) Same defects at 50X.

(a)

(b)

Figure 2. (a) SMA deposited stainless steel cladding showing Type S2 defect (longitudinal defect between weld passes) at 5X. (b) Same defect at 50X.

(a)

(b)

Figure 3. (a) SMA deposited stainless steel cladding showing Type S3 defect (transverse defect at weld starts) at 5X. (b) Same defect at 50X.

SMA Deposited Stainless Steel Cladding Defect Density vs. Defect Size

Figure 4. SMA deposited stainless steel cladding defect size distributions for the three defect types evaluated. The results shown are extrapolated to 28317 cc (one cubic foot) of cladding.

Figure 5. (a) GTA-HW deposited nickel-chromium alloy EN82H cladding showing Type E1 (pore-like) defect and Type E3 (tight) defect at 50X as polished condition. (b) Same defects at 50X etched condition.

(a)

(b)

Figure 6. (a) GTA-HW deposited nickel-chromium alloy EN82H cladding showing Type E2 (crevice-like) defect at 50X as polished condition. (b) Same defect at 50X etched condition.

Weld Deposited Cladding Distributions

Figure 7. Comparison of the defect size distributions for both the GTA-HW deposited EN82H cladding and the SMA deposited stainless steel cladding.