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Influence of Crack Dimensions and Heat Treatment on Fracture Behaviour of AA1050 Alloy Pipes Subjected to Bursting Pressures

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Abstract—There are different codes and standards for assessing pipeline flaws depending on the type of flaw. Corrosion is commonly assessed using ASME B31G, DNV-RP-F101, SHELL-92, RSTRENG. The Finite Element method is becoming popular for evaluation of crack and corrosion flaws. In this paper 3D finite element analysis and Taguchi technique were employed to investigate fracture criteria of AA1050 Al-alloy pipes subjected to internal bursting pressure. The yield strength criterion was used to study the failure of pipes. It was observed that the J-integral was proportional to the deformation under the applied bursting pressure. It was noticed that the major dominating control factors which could influence the failure of pipes were the pipe thickness and heat treatment process.

Keywords— AA1050 Al-alloy, bursting pressure, crack length, crack depth, heat treatment, finite element analysis.

I. INTRODUCTION

Pipelines must be safe and efficient for transporting high volumes of oil and gas. However, aged pipelines may experience flaws, such as cracks or corrosion. AA1050 alloy is known for its excellent corrosion resistance, high ductility and highly reflective finish. AA1050 alloy is typically used for chemical process plant equipment. The codes such as ASME B31G [1] DNV-RP-F101 [2], SHELL-92 [3], and RSTRENG [4], are the semi-empirical methods used for the assessment of the integrity of pipes. The finite element analysis (FEA) is one of the most efficient tools to quantify reliably the remaining strength of corroded pipes. Elastic-Plastic finite element models have been used to provide more accurate results in evaluating the corrosion defects as reported [5]-[8].

The present work was aimed at to study the finite element analysis of crack propagation and bursting with predefined flaws of varying length and depth in AA1050 Al-alloy pipes.

II. MATERIALS AND METHODS

The material of pipes was AA1050 Al-alloy. The chosen control parameters are summarized in table 1. The orthogonal array (OA), L9 was selected for the present work [9]. The control factors were assigned to the various columns of O.A. The assignment of control factors along with the OA matrix is given in table 2. A surface notch as shown in Fig. 1(a) made on the outer surface of the pipe specimen. The dimensions of notch are given in Fig.1(b).

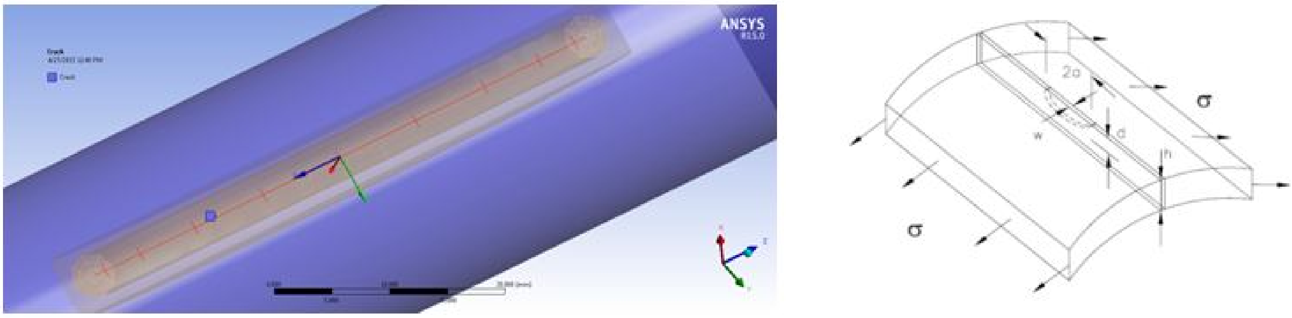
TABLE 1
CONTROL FACTORS AND THEIR LEVELS

Factor	Symbol	Level–1	Level–2	Level–3
Thickness, mm	A	1.0	1.2	1.5
Length of crack, mm	B	25	50	75
Depth of crack	C	40%t	50%t	60%t
Heat treatment	D	H14	H16	H18

where *t* is pipe thickness

TABLE 2
ORTHOGONAL ARRAY (L9) AND CONTROL FACTORS

Treat No.	A	B	C	D
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1



(a) (b)

Fig. 1. Surface notch created on the pipe(a) and crack dimensions (b).

The operating pressure calculation was obtained from ASME B31.8 [10]:

$$P = (2\,\sigma t)/D \times F \times E > \quad (1)$$

where P is the design pressure (MPa), σ is the specified minimum yield strength (MPa), t is the nominal wall thickness (mm), D is the nominal outside diameter (mm), F is the design factor, E is the longitudinal joint factor and T is the temperature derating factor.

The cross-section of the pipe was created in 2-D and then it was extruded for the given pipe length along the z-direction. The ANSYS code was used to model the pipe and initial semi-elliptical crack. The pipe was modeled with tetrahedron elements. Fracture module method for crack generation required that elements be of higher order. Therefore, out of choice of tetrahedral elements of type SOLID 186 were chosen for accurate results [11]. Fine mesh was used to model the crack region. The number of elements and nodes were 1,20,442 and 2,50, 108 respectively. A three-dimensional semi-elliptical crack was initiated on the shaft surface. The crack was oriented with respect to pipe axis. In order to create the semi-elliptical crack onto to the surface, a local coordinate system was established. With reference to the local co-ordinate system and the crack was created on the outer surface of the pipe as shown in Fig. 2. The pressure obtained from Eq. (1) was applied on the inner surface of pipe.

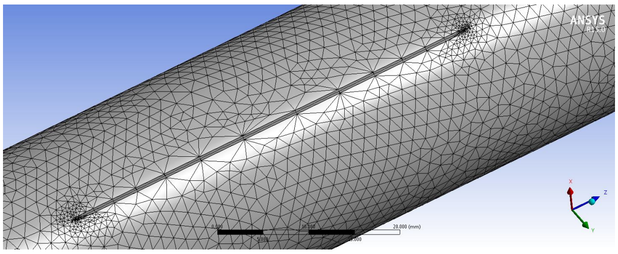


Fig. 2. Mesh view of crack on the pipe surface.

If the failure is defined by material yielding, it follows that the design goal is to limit the maximum equivalent stress to be less than the yield strength of the material:

$$ES/YS < 1 \quad (2)$$

where, *ES* is the equivalent stress and *YS* is the yield strength of AA1050 Al-alloy.

III. Results and Discussion

The finite element software was carried out twice with two mesh densities according Taguchi design of experimentation.

A. *Static Deformation*

Fig. 3 gives the total deformation values of tested pipes with different crack geometry and bursting pressure. It was observed that the maximum total deformation of 0.0195 mm with trial no.3 and the minimum total deformation of 0.00365 mm with trail no.9. For trials 3 and 9 the thicknesses were 1 mm and 3 mm respectively.

B. *Equivalent Stress Distribution Across the Crack*

The equivalent stress distribution across the crack for all the test coupons is shown in Fig. 4. The maximum equivalent stress of test coupons 1, 2, 3, 4, 5, 6, 7, 8 and 9 were found to be 108.11 MPa, 166.53 MPa, 266.07 MPa, 201.95 MPa, 86.31 MPa. 125.73 MPa, 108.97 MPa, 109.53 and 64.95 MPa respectively. The equivalent stresses of trials 1, 5 and 9 were belonging to heat treatment, H14. For trail 1 only the equivalent stress exceeded the yield strength (103 MPa) of AA1050. The equivalent stresses of trials 2, 6 and 7 were belonging to heat treatment, H16.

For trail 7 only the equivalent stress did not exceed the yield strength (124 MPa) of AA1050. The equivalent stresses of trials 3, 4 and 8 were belonging to heat treatment, H18. For trail 8 only the equivalent stress did not exceed the yield strength (145 MPa) of AA1050.

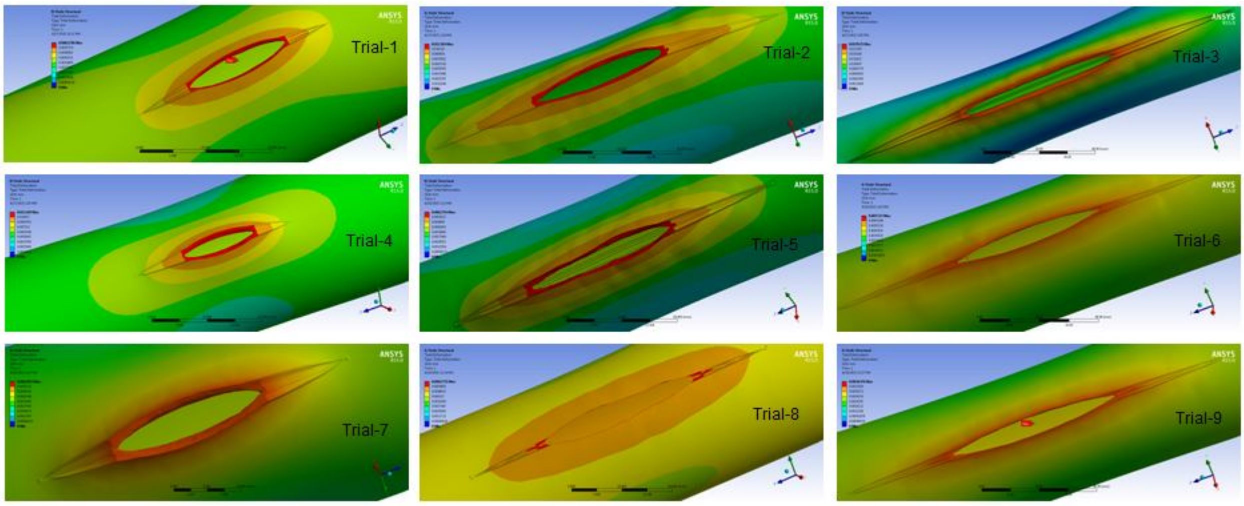


Fig. 3. Total deformation of test coupons.

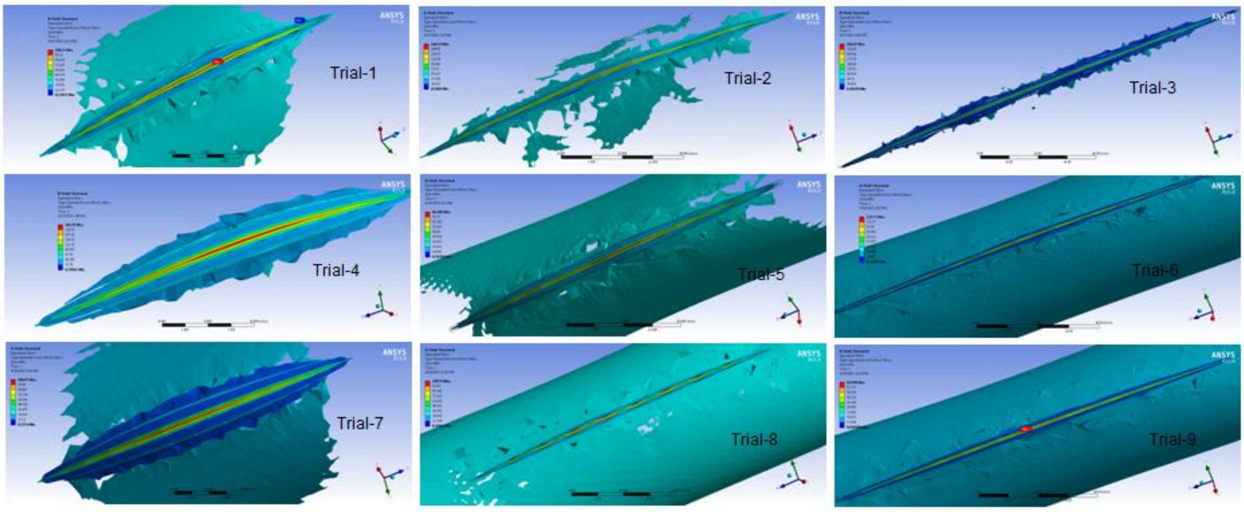


Fig. 4. Equivalent stress along crack front.

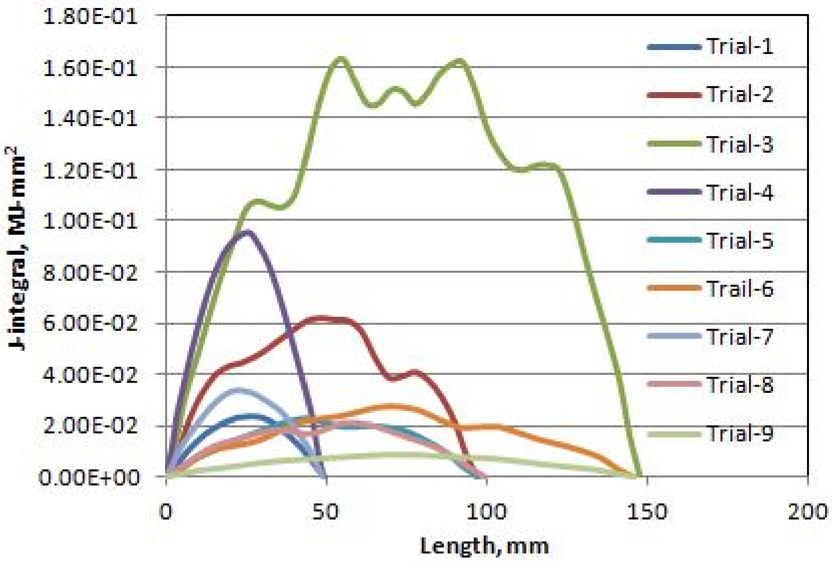


Fig. 5. J-Integral values of all trials.

C. J-integral

The path dependence of the J-integral is displayed for all nine specimens are shown in Fig. 5. The maximum value of J-integral was 0.16329 MJ/mm^2 with third trial having the displacement of 0.0195 mm. The minimum value of J-integral was 0.008724 MJ/mm^2 with ninth trial having the displacement of 0.00365 mm. Therefore, the J-integral was directly proportional to the displacement of the load applied on the pipe. The path dependence of the J-integral was much more significant in a large deformation analysis [12]. The far field value of J was reached with test coupon 3 latter, whereas in the test coupon 9 having small deformation the far field value of J was already reached.

D. Stress Intensity Factors

Each test coupon was started with a pre-existing crack of a given length "2a". Mode I was a spreading apart of the two halves of the crack interface, recognizable as the most severe case. Fig. 6 shows the variations of stress intensity factor, KI along the initial crack-front for all pipes. The stress intensity factors, KII and KIII are not highly influential factors as compared stress intensity factor KI. The pipe 3 has the maximum value (114.01) of KI whereas the pipe 9 has the minimum value (26.42) of KI.

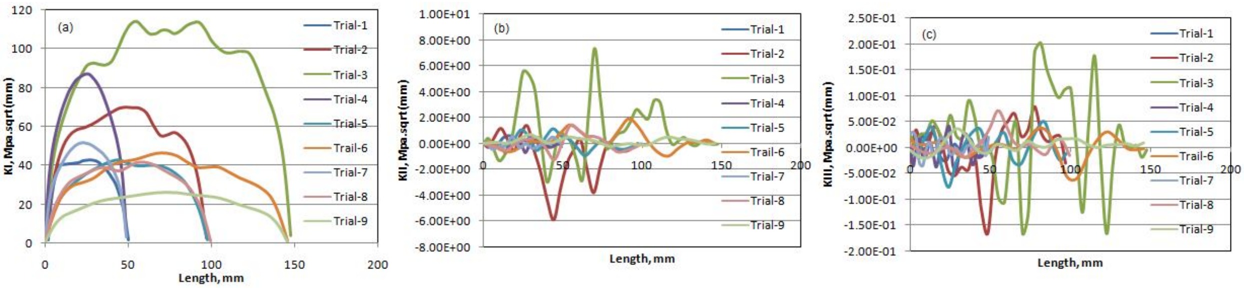


Fig. 6. Stress intensity factors: (a) KI, (b) KII and (c) KIII values of all trials.

E. Failure Criteria

The ANOVA summary of yield strength (YS) failure criterion is given in table 3. The Fisher's test column ascertains the parameters (A, B, C and D) accepted at 90% confidence level influencing the variation in the impact strength. The percent contribution indicates that the thickness of the pipe only contributed 56.27% of the variation for YS criterion respectively. The crack length (B) put in 4.85% of variation for YS criterion. The crack depth (C) gave 8.33% of variation for YS criterion. The heat treatment (D) aids 30.99% of variation for YS criterion.

TABLE 3- ANOVA SUMMARY OF THE YS FAILURE CRITERIA

Source	Sum 1	Sum 2	Sum 3	SS	v	V	F	P
A	8.47	6.48	4.52	1.29	2	0.645	1089.02	56.27
B	6.62	5.88	6.97	0.11	2	0.055	92.86	4.85
C	5.64	6.73	7.10	0.19	2	0.095	160.40	8.33
D	5.06	6.91	19.47	0.71	2	0.355	599.38	30.99
Error				0.0053305	9	0.0005923	1.00	-0.44
T	25.79	26.00	38.05	2.2946695	17			100

The effect of pipe thickness on the failure criteria is depicted in figure 7a. It is noticed that the failure of pipes decreases with an increase in the pipe thickness. The failure was minimal for the pipes undergone the heat treatment H14 (figure 7b). This was owing to the reduction of ductility as a result of heat treatment. The elongations of AA1050 Al-alloy were 10%, 8% and 7% respectively for H14, H16 and H18 heat treatments. These are strain hardening processes only. The failure criteria are plotted for all the test coupons in figure 8. The test coupons 5, 7, 8 and 9 are satisfactory under YS failure criteria.

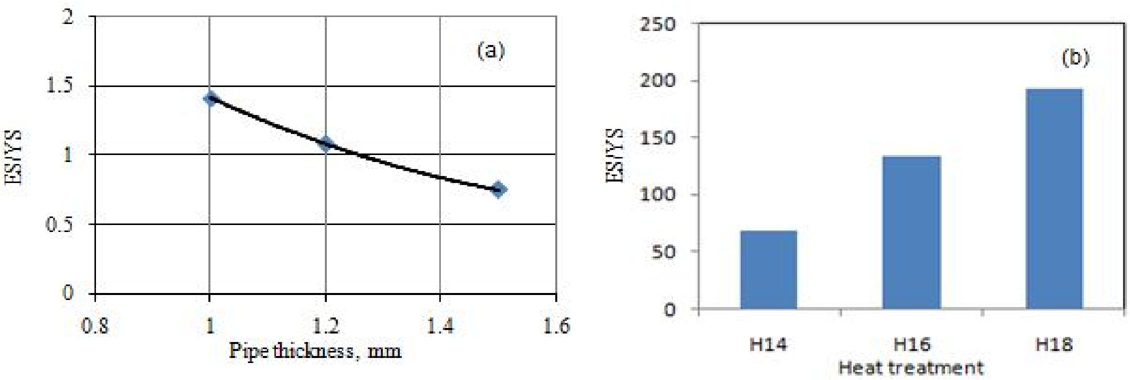


Fig. 7. Effect of pipe thickness (a) and heat treatment on the failure criterion.

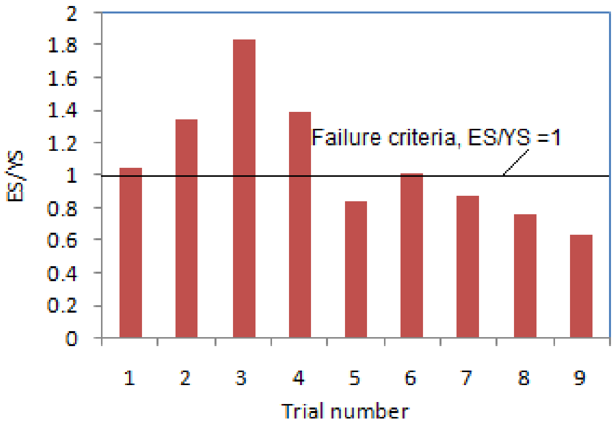


Fig. 8. Failure criteria of all test coupons.

IV. Conclusions

The failure of pipes decreases with the increase of pipe thickness. The strength of AA1050 Al-alloy increases with strain hardening processes H14, H16 and H18. However, the ductility decreases. The failure of pipes under bursting pressure was low for the pipes treated with H14 because of high ductility as compared to H18 heat treatment. The J-integral is directly proportional to the displacement of the load applied on the pipe. As per yield strength failure criteria, the failure was low for the pipes having 1.5 mm thickness, 75 mm crack length, 0.75 mm crack depth and heat treated under H14 conditions.

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