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Influence of Crack Size on Fracture Behavior of Heat Treated 2011 Al-Alloy Pipes Using Finite Element Analysis

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Abstract: ***The assessment of cracks in the gas pipe lines is very important with respect to safety. In this paper 3D finite element analysis and Taguchi technique were employed to investigate fracture criteria of AA2011 Al-alloy pipes subjected to different internal bursting pressures. The ultimate tensile strength criterion was employed to study the failure of pipes. The major dominating control factors were crack length and heat treatment of the pipes.***

Keywords: AA2011 Al-alloy, bursting pressure, crack length, crack depth, heat treatment, finite element analysis.

1. Introduction

Prediction of the bursting pressure of a gas or liquid pipe lines is an important consideration in its design for its safety and reliability. Standing for the maximum load-bearing capacity of the pipe, the burst pressure is generally defined as the ultimate load or failure pressure of a pipe at plastic collapse. Aluminum alloy 2011 is used in applications that require parts manufactured by repetition machining. AA2011 Al-alloy is susceptible to corrosion. Hence, it is necessary to estimate the withstanding capacity of heat treated AA2011 Al-alloy pipes subjected to different bursting pressures. Numerous methods have been developed for predicting the burst pressure of blunt part-wall defects, which characterize the behavior of typical corrosion defects [1, 2, 3, 4]. ASME B31G, DNV-RP-F101, SHELL-92 and RESTRENG were applied to assess the strength of thin tubes [5, 6, 7, 8]. 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 [9, 10, 11].

The objectives of the present work were to evaluate the influence of crack dimensions and heat treatment on the bursting pressure of AA2011 Al-alloy pipes using finite element analysis and Taguchi techniques.

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	30%t	40%t	50%t
Heat treatment	D	T6	T3	T8

where t is pipe thickness

2. Materials and Methods

The material of pipes was AA2011 Al-alloy. The chosen control parameters are summarized in table 1. The control factors were assigned to the various columns of orthogonal array (OA), L9 is given in table 2. The pipe model and surface crack were modeled using computer aided design tools [12]. A surface notch made on the outer surface of the pipe specimen. The dimensions of notch are given in figure 1.

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

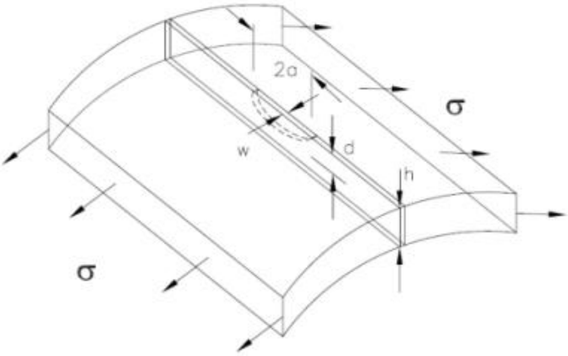

Figure 1: The Crack dimensions.

The operating pressure was obtained from the following expression:

$$P = 0.60\,\sigma_y(2t/D) \times (1 - t/d) \tag{1}$$

where P is the design pressure (MPa), σ_y is the yield strength (MPa), t is the nominal wall thickness (mm), D is the nominal outside diameter (mm), and d is the crack depth.

The ANSYS code was used to estimate the stresses induced in the pipes under applied pressure for predefined crack dimensions and type of heat treatment. The pipe was meshed with tetrahedron elements [13]. A three-dimensional semielliptical crack was initiated on the pipe surface. The crack was oriented with respect to pipe axis as shown in figure 2. The pressure obtained from Eq. (1) was applied on the inner surface of pipe.

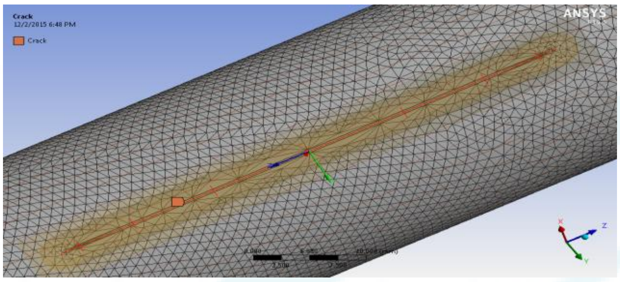

Figure 2: Meshing of crack and pipe.

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

$$ES/UTS < 1 \qquad (2)$$

where, ES is the equivalent stress and UTS is the yield strength of AA2011 Al-alloy.

3. Results and Discussion

The finite element analysis was carried out twice with two element sizes of 1.0 mm and 1.5 mm density according Taguchi design of experimentation.

3.1 Static deformation

The total deformations of analyzed pipes are shown in figure 3. For the pipes having thickness of 1mm the maximum total deformation of 0.0382 mm was observed with test coupon 3 and the minimum total deformation of 0.0211 mm test coupon 1. For the pipes having thickness of 1.2 mm the maximum total deformation of 0.0315 mm was observed with test coupon 4 and the minimum total deformation of 0.0235 mm test coupon 6. For the pipes having thickness of 1.5 mm the maximum total deformation of 0.0289 mm was observed with test coupon 8 and the minimum total deformation of 0.0237 mm test coupon 9.

3.2 Equivalent stress distribution across the crack

The equivalent stress distribution across the crack for all the pipes is shown in figure 4. The maximum equivalent stress of test coupons 1, 2, 3, 4, 5, 6, 7, 8 and 9, respectively 421.10 MPa, 449.86 MPa, 1125.90 MPa, 618.03 MPa, 397.86 MPa, 570.14 MPa, 474.37 MPa, 572.94 and 518.14 MPa. The equivalent stresses of the pipes 1, 5 and 9 were belonging to heat treatment, T6. For the pipe 5 only the equivalent stress was not surpassed the ultimate tensile strength (399 MPa) of AA2011 Al-alloy. The equivalent stresses of the pipes 2, 6 and 7 were belonging to heat treatment, T3. For the entire pipes the equivalent stress went beyond the ultimate tensile strength (379 MPa) of AA2011 Al-alloy. The equivalent stresses of trials 3, 4 and 8 were belonging to heat treatment, T8. For all pipes the equivalent stress was exceeded the ultimate tensile strength (407 MPa) of AA2011 Al-alloy.

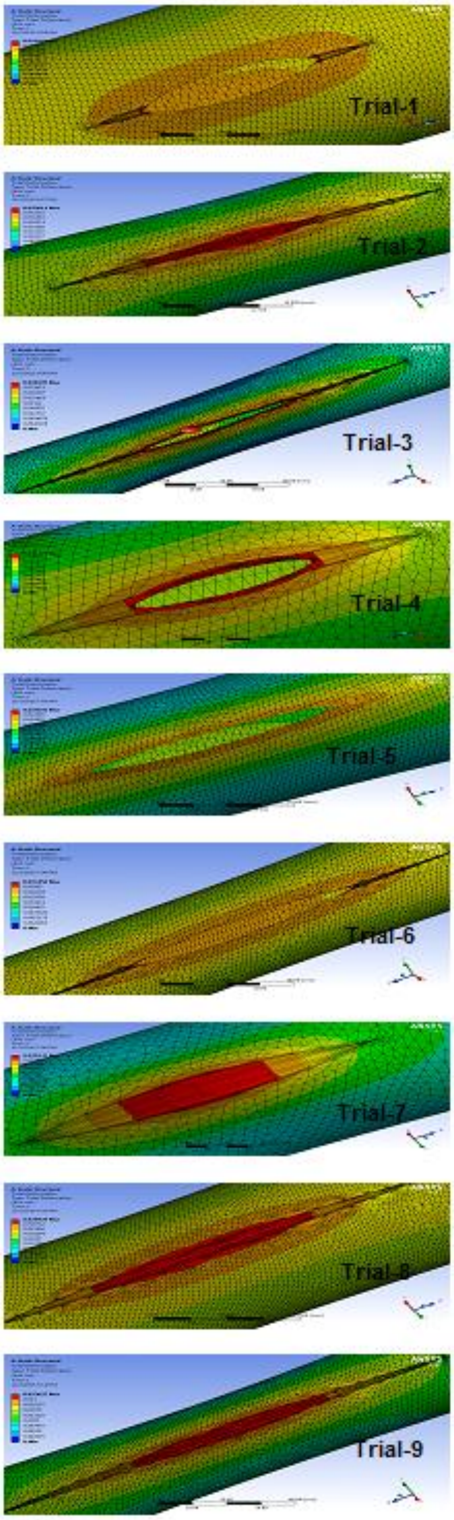

Figure 3: Total deformations of all test coupons.

3.3 J-integral

The path dependence of the J-integral is displayed for all nine pipes in figure 5. The maximum values of J-integral were 0.691, 0.697 and 0.676 MJ/mm^2 with the pies 3, 4 and 7 respectively having the displacements of 0.0382, 0.0315 and 0.0282 mm. The minimum value of J-integral was 0.220 MJ/mm^2 with the test coupon 1 having the displacement of 0.0211 mm. Therefore, the J-integral is 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 [14].

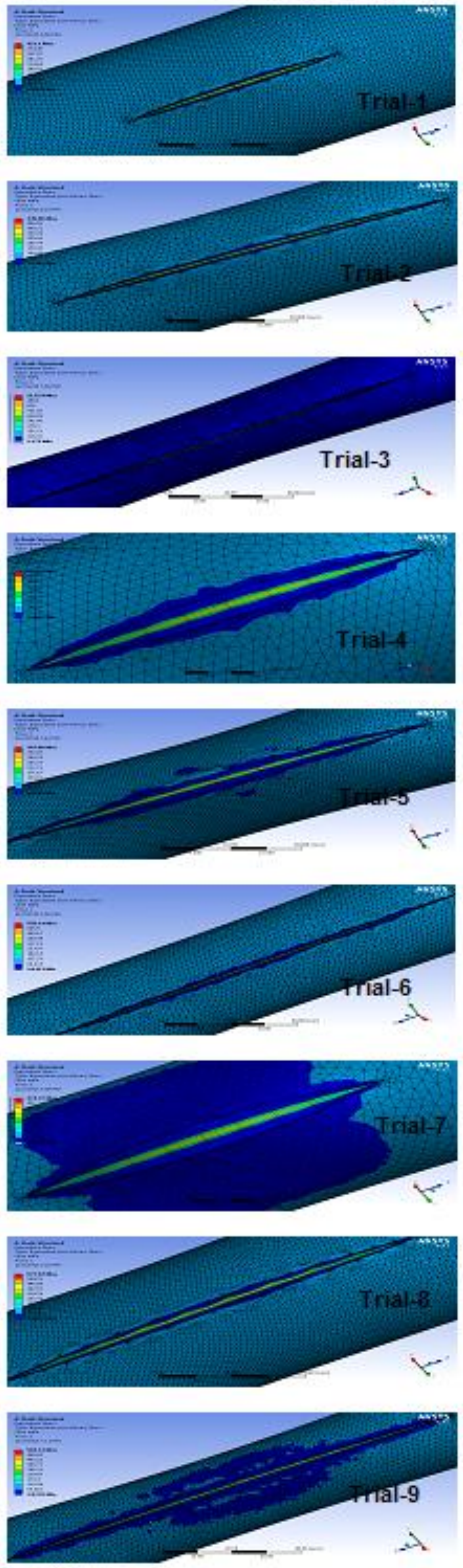

Figure 4: Equivalent stresses of all test coupons

3.4 Stress intensity factors

Figure 6 shows the variations of stress intensity factor, KI along the initial crack-front for all pipes. The KI had the maximum values of 233.00, 234.28 and 230.09 MPa-sqrt(mm) respectively for the pipes 3, 4 and 7. The stress intensity factors, KII and KIII were found insignificant.

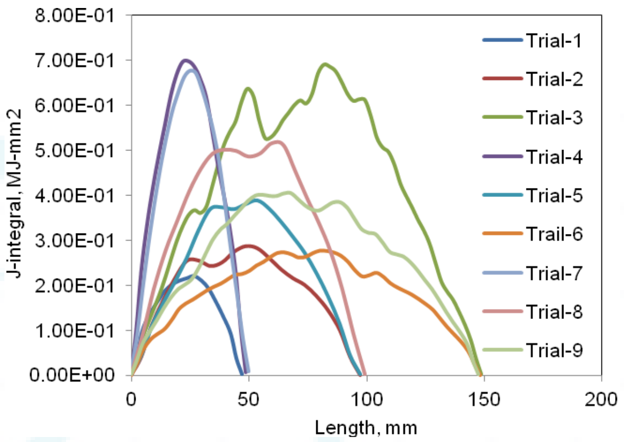

Figure 5: J-Integral values of all test coupons.

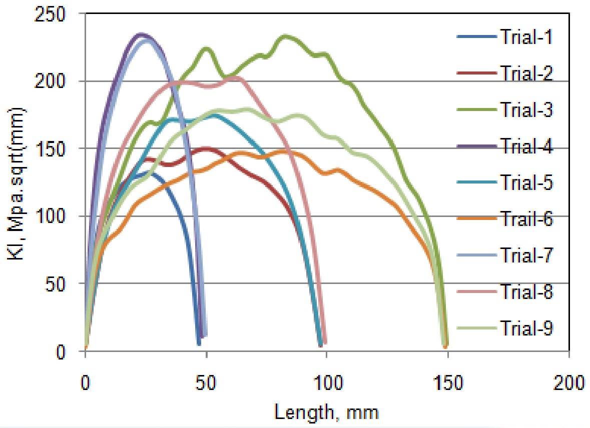

Figure 6: Stress intensity factors, KI of all test coupons.

3.5 Failure Criteria

The ANOVA summary of ultimate tensile strength (UTS) failure criterion is given in table 3. All parameters were accepted at 90% confidence level. The percent contribution indicates that the heat treatment of the pipes contributed 43.40% of the variation for the UTS criterion. The second major contribution (35.96) was of the crack length. The influences of crack depth (C) and pipe thickness (A) were very low.

Table 3: ANOVA summary of the UTS failure criteria

Source	*Sum 1*	*Sum 2*	*Sum 3*	*SS*	*v*	*V*	*F*	*P*
A	10.06	7.96	7.93	0.49	2	0.245	93.68	10.6
B	7.66	7.10	11.20	1.65	2	0.825	315.45	35.96
C	7.96	8.04	9.96	0.42	2	0.21	80.30	9.07
D	6.68	10.37	25.96	1.99	2	0.995	380.45	43.4
Error	32.36	33.46	55.05	0.02354	9	0.00262	1.00	0.97
T	32.36	33.46	55.05	4.57354	17			100

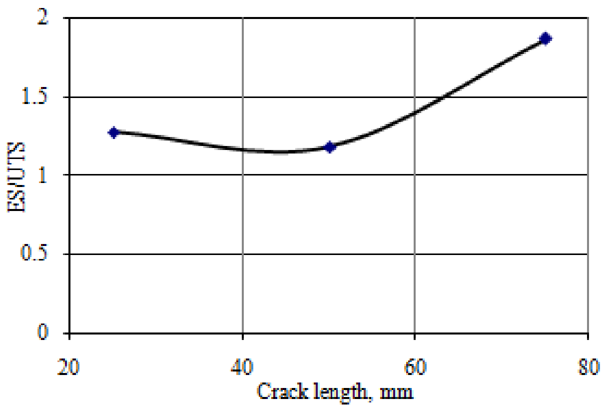

Figure 7: Effect of crack length on the failure criterion

The effect of crack length on the failure criteria is shown in figure 7. The failure of pipes was high at crack length of 75 mm. The failure of pipes having crack lengths of 25 mm and 50 mm was not much invariant. The failure was minimal for the pipes undergone the heat treatment T6 (figure 8). The optimum conditions of test coupon 5 would satisfy the failure criterion (ES/UTS = 0.997 <1.0) while all other conditions were failed to satisfy the failure criterion.

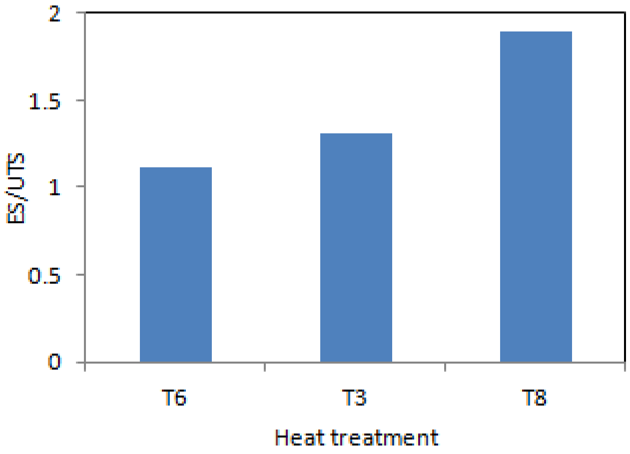

Figure 8: Effect of heat treatment on the failure criterion.

4. Conclusions

The failure of pipes increases with the increase of crack length. The failure of pipes under bursting pressure was low for the pipes heat treated with T6 conditions.

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