［溶接学会論文集　第 38 巻　第 2 号　p. 159s-162s （2020)］

Effect of blowholes on fatigue crack initiation life of aluminum alloy lap-joint*

by TSUTSUMI Seiichiro**, DAIMON Gaku *** and FINCATO Riccardo**

Blowhole (BH) contained in weld joints is known to be a cause of reduction in strength. Concerning the effect of BHs to fatigue performance of weld joints, their total number or volume are conventionally used for the mechanical design, since the available data are limited by the measuring precision and their costs. In other words, the mechanical design would be improved if the individual size or position of the BHs could be precisely determined since it would lead to a better knowledge of the material performance and therefore to a more precise maintenance of the welded components. The purpose of this study is to develop a fatigue performance evaluation method for aluminum alloy joints considering the effect of BHs. Several FE models of lap welded joints, with different BH distributions, were generated to simulate the BH effects under fatigue loading. The material model adopted for FE analyses is based on an unconventional plasticity model, calibrated to reproduce the cyclic plasticity behavior of aluminum A5083-O. The numerical local stress-strain relationship is analyzed in correspondence to the area with the higher plastic deformation. Therefore, the fatigue crack initiation life was calculated using a formula based on the experimental database. Predicted S-N curve on crack initiation life revealed that BHs in some cases would reduce the fatigue strength. Also, there was a significant correlation between the crack initiation life and the normalized distance between the toe and the BHs.

Key Words: blowhole, fatigue crack, weld joint, FEM, elasto-plasticity

1. Introduction

Fatigue damage has been recognized as one of the critical issues in components and structures. Particularly, the fatigue phenomenon is crucial in welded joints, where the stress tends to concentrate. Moreover, factors such as blowholes and poor penetration in welding are known to reduce the fatigue performance of joints.

Aluminum alloys are used for bridges and vehicles because of their lightweight and excellent corrosion resistance properties. However, BH tends to occur easily in aluminum materials. In general, concerning the effect of BHs, the total number or volume of BHs are conventionally used for the mechanical design in fatigue performance of weld joints[1]. It should be noted that this design method does not consider the size nor the position of individual BHs. The reason why this kind of design method is adopted is due to the fact that an experimental characterization of the presence and location of the BHs is not easy due to the problem of reproducibility of the manufacture and the high cost of fatigue testing itself. For these reasons, the current design method might be a standard too conservative and it prescribes frequent welding repairs. On the other hand, recent advances in non-destructive inspection technologies (i.e. computed tomography, ultrasonic testing, etc.) have highly improved the detection capabilities of BHs. So it is expected to realize an accurate fatigue performance evaluation method by means of the latest measurement technologies together with numerical simulations.

Previous works[2)-5)] have been conducted to understand the effect of BH on the fatigue strength. However, the effects of BH on fatigue life of aluminum joints are not clear enough, and the mechanism underlying it remains to be understood. The authors of the present paper have been developed an evaluation method of fatigue life of welded joints by using nonlinear FE analysis incorporating a novel cyclic elastoplasticity model. The cyclic plasticity model and the evaluation scheme of fatigue crack initiation life have been applied to investigate several engineering problems up to the present. The purpose of this study is to establish an evaluation method of the effect of a BH on fatigue performance in aluminum alloy joints based on nonlinear FE analyses incorporating a novel cyclic elastoplasticity model.

2. FE models and boundary condition

In order to evaluate the BH effect on the fatigue crack initiation life of the aluminum joints, cyclic elastoplastic FE analyses incorporating a novel model[4)] were performed to simulate the BH effects under fatigue loading against 2D and 3D FE models that reproduce the experimental test specimens.

In the 2D simulations, several FE models of welded joints with different BH distributions were created (see Fig. 1). Three different BH diameters were considered in the numerical modeling d = 0.2, 0.5, and 1.0 mm, respectively. A total number of eight models with different BH distributions were created (w/o BH, d0.2_x0.16,

---

[*] Received: 2019.11.21, Presented at Visual-JW or WSE 2019

[**] Member, Joining and Welding Research Institute Osaka University

[***] Student Member, Graduate school of Engineering Osaka University

d0.2_x0.4, d0.5_x0.26, d0.5_x0.4, d0.5_x1.0, d1.0_x0.8, d1.0_x2.0). The FE models consider a 2D geometry under the assumption of a plane strain condition. The areas around the weld toe and the BH, where the stress tends to localize, were meshed with fine elements (i.e. minimum element size of 50μm). The constitutive equations of the elastoplastic model, named Fatigue-SS model[6)], were implemented via user subroutine for the commercial software ABAQUS and used to investigate the cyclic plastic behavior of aluminum alloy A5083-O.

An initial calibration of the model parameters was performed, reproducing the experimental monotonic tensile tests realized by Horikawa *et al*[7)]. The results are reported in Fig. 3 and Fig. 4. The black dashed lines indicate the experimental results and the solid blue lines show the calculated stress-strain relationships. The graphs display that the predicted stress-strain responses are almost equivalent to the experimental results. A cyclic load was applied to the sample as indicated in Fig. 1, performing 100 cycles under constant nominal stress range and with a stress ratio R=0 (i.e. unidirectional cyclic loading).

For sake of simplicity, and due to the symmetry of the geometry, the 3D modeling was realized considering half sample as shown in Fig. 2. Similarly to the 2D model, a reference case for the three dimensional analyses was created without the presence of a BH. An additional FE model was created considering a spherical BH with a diameter d of 0.5 mm. The BH was placed on the symmetry plane at a distance x = 0.26 mm from the toe. The analyses

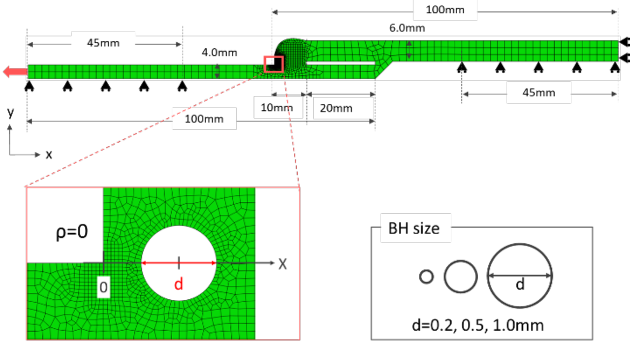


Fig. 1　FE model (2D)

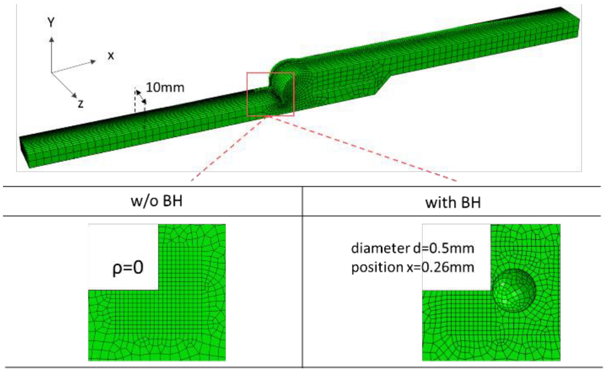


Fig. 2　FE model (3D)

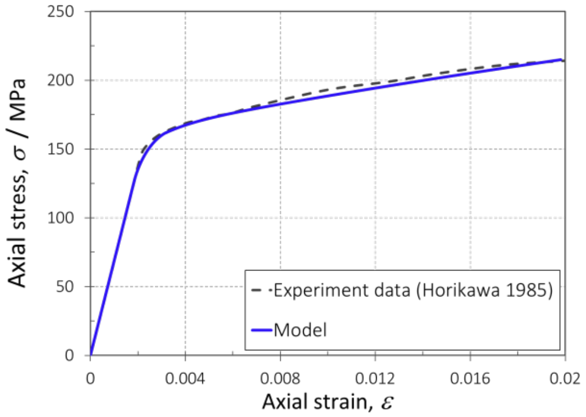


Fig. 3　Comparison between the model response and the experimental results (tensile stress-strain curve)

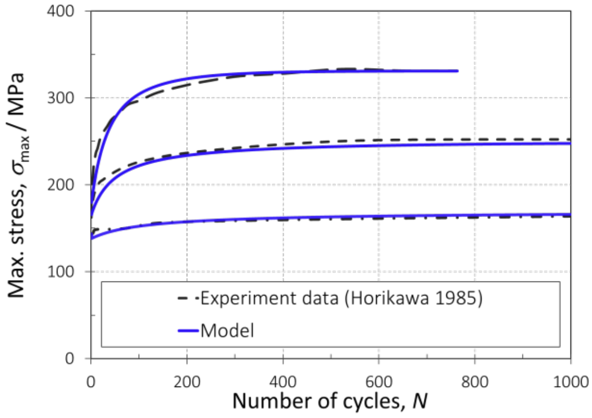
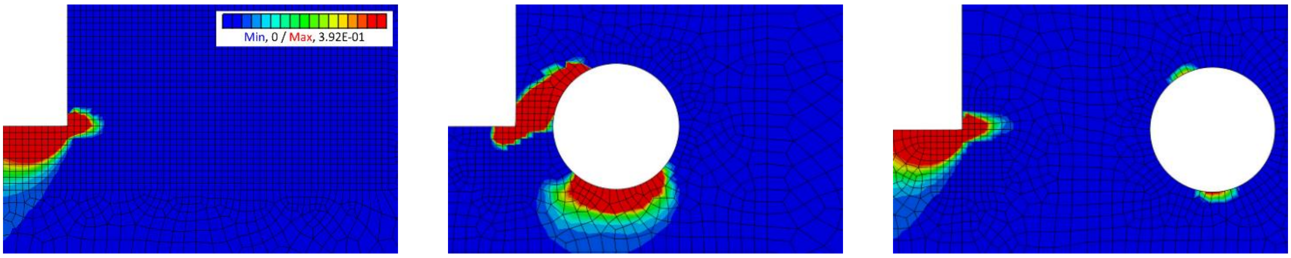


Fig. 4　Comparison between the model response and the experimental results (Max stress vs number of cycles)

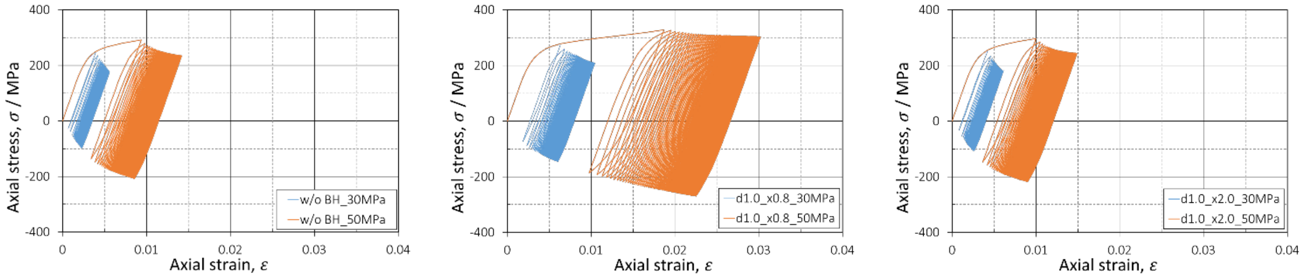


w/o BH　　d1.0_x0.8　　d1.0_x2.0

Fig. 5　Distribution of the cumulative plastic strain conditions are the same as for 2D analyses.

3. Numerical results

Firstly, the results of 2D analyses are discussed. Fig. 5 shows the distribution of cumulative equivalent plastic strain for the three representative models. This figure shows that the plasticization is particularly relevant at the weld toe and around the BH, where the stress is concentrated. It can also be seen that the closer the BH position is to the toe, the higher is the plasticity around the BH. This aspect can be explained by the mutual interaction between the BH and the toe geometry that enhances the formation of irreversible deformations. Fig. 6 shows the results obtained for each model in terms of local stress-strain curves. In detail, the stress-strain curves are representative of the elements with the highest plastic accumulation, where the crack is expected to initiate. The effect of the BH can be observed. The plastic strain accumulation and the axial stress amplitude seem to be highly affected by the presence of the BH. It can also be seen that the strain magnitude is higher when the BH position is closer to the toe. In all models, the hysteresis loop size in terms of total strain range tends to saturate to a constant value. An additional comparison is offered in Fig. 7 where the evolution of the total strain range is reported for the model without BH. The blue and orange lines represent the results when the nominal stress range is 30MPa and 50MPa, respectively. The fatigue crack initiation life Nc was



w/o BH d1.0_x0.8 d1.0_x2.0

Fig. 6 Relationship between stress and strain

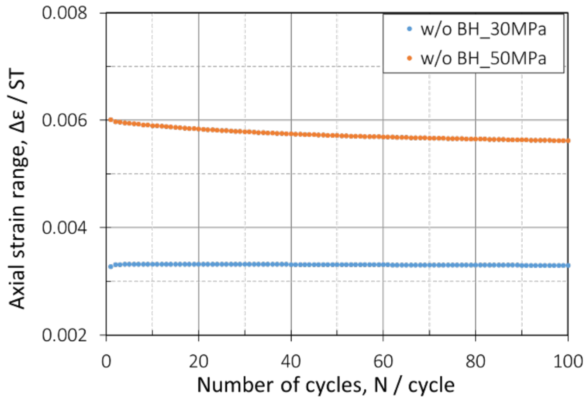


Fig. 7 Evolution of the strain range

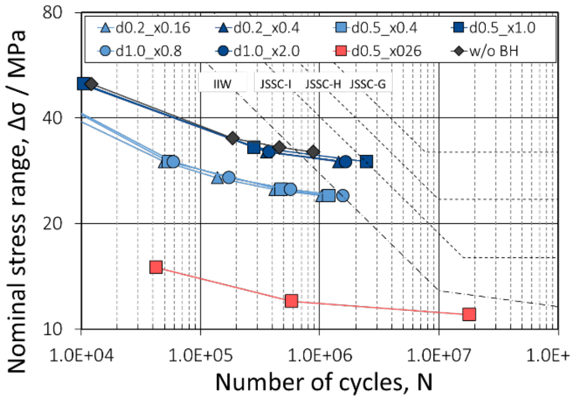


Fig. 8 S-N curve (2D)

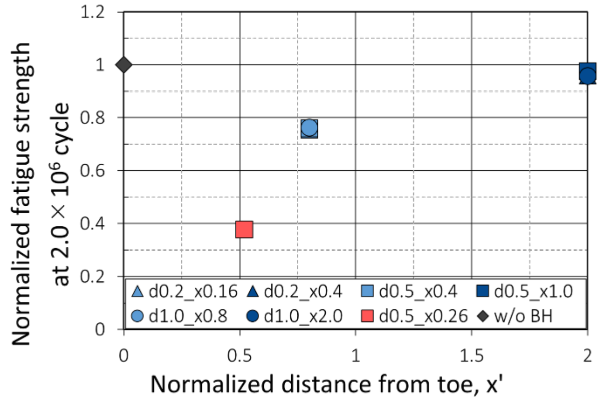


Fig. 9 Fatigue strength at 2x10^6 cycles for different combinations of *d* and *x*

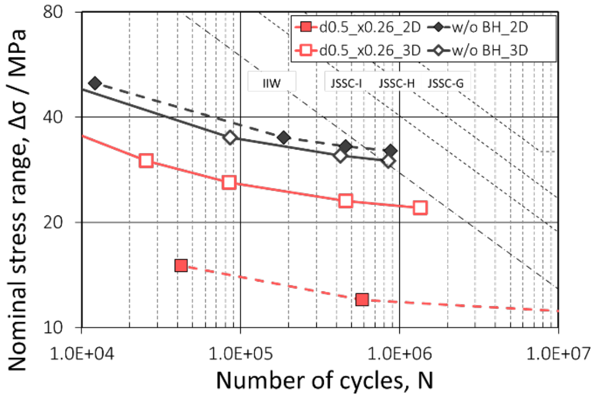


Fig. 10 S-N curve (2D and 3D)

evaluated using the method reported in a previous study[8), based on the strain range magnitude $\Delta\varepsilon_t$ along the maximum principal strain direction and on an experimental database. In this study, the following equation is used.

$$\Delta\varepsilon_t / 2 = 11.9Nc^{-0.475} + 0.168 \quad (1)$$

The results are shown in Fig. 8, where the predicted S-N curves for the crack initiation life are reported. For sake of comparison 8 curves are reported, considering different combinations of the diameter *d* of the BH and its distance from the weld toe *x*. It is concluded that the presence of BHs, in some cases, would reduce the fatigue strength with a rate of reduction that varies depending on the combination of *d* and *x*. Fig. 9 shows the relationship among the fatigue strength at $2x10^6$ cycles of each model. On the y axis, it is reported the fatigue strength normalized against the fatigue strength at $2x10^6$ cycles of the sample without BH. On the x axis, is reported the normalized distance of the BH from the toe (i.e. X' = x/d, see Fig. 1). Fatigue strength tends to decrease for lower values of the normalized distance X'. Therefore, the fatigue strength shows a decreasing tendency with large diameters of the BH and with small distances of the BH from the welding toe. A significant correlation was observed between the normalized distance and fatigue strength.

Secondly, the results of 3D analyses are shown. Fig. 10 shows the predicted S-N curves for the crack initiation life obtained from 3D analyses. For sake of comparison 4 curves are reported, considering the presence of the BH and geometry (2D plane strain and 3D). In this figure, 2D results are shown as solid mark, whereas 3D results are shown as empty marks. The 3D analyses confirmed the results obtained in the 2D cases that the fatigue strength is decreased by the presence of BHs. However, due to the difference in the BHs' shape, the reduction rate is smaller in the 3D analyses than in the 2D analyses. In the 2D analyses, the BH was modeled considering the sample under the assumption of a plane strain condition, whereas in 3D analysis a spherical BH is modeled. This aspect is quite relevant and it influences the strength of the joint and the generation of plastic deformation during the analyses. Therefore, the 2D model seems to consider an excessively large defect, leading to a lower fatigue life compared with the 3D case. At the same time, this remarks the importance of considering 3D shape of a BH.

4. Conclusions

The present work aimed to establish an evaluation method of the effect of a BH on the fatigue performance in aluminum alloy joints. Numerical simulations were carried out by using 2D and 3D models. The results can be summarized as follows.

1) The present results suggested that BH reduces fatigue strength. Moreover, the fatigue strength shows a decreasing tendency with larger values of the diameter of the BH and with small distances of the BH from the welding toe.

2) A significant correlation could be observed between the normalized distance and fatigue strength. So, the normalized distance X' may be an effective parameter to evaluate the fatigue strength of joints containing BH.

3) In evaluation of the BH effect on fatigue life, it is important to consider 3D geometry.

For the purpose of studying more realistic conditions, it is expected to conduct, in the future works, analyses of 3D model containing multiple BHs and evaluation of fatigue crack propagation life after initiation.

Reference

1) IIW: Fatigue Design of Welded Joints and Components, XIII-1539-96 / XV-845-96, 1996.

2) O. Kuwazuru, et al.: Quantitative Evaluation of Porosity Effect on Fatigue Strength of High Pressure Die Cast Aluminum Alloy (Part 2, Fatigue Strength Prediction Based on Elastic Stress Field around Pores), Transactions of the Japan Society of Mechanical Engineers Series A, Vol. 77, No. 773(2011), pp. 48-57

3) K. Yamada, S. Miyakawa, S. Yosikawa, A. Hasimoto: Effect of Casting Defect on the Fatigue Strength of Aluminum Die Casting Materials. Transactions of the Japan Society of Mechanical Engineers Series A, Vol. 68, No. 667(2002), pp. 137-143

4) L. Qian, et al.: Cyclic deformation fields interactions between pores in cast high manganese steel, International Journal of Plasticity 112(2019), 18-35

5) Q. Deng, N. Bhatti, X. Yin, M. Wahab: Numerical Modeling of the Effect of Randomly Distributed Inclusions on Fretting Fatigue-Induced Stress in Metals, Metals, 2018, 8(10):836

6) S. Tsutsumi, R. Fincato: Cyclic plasticity model for fatigue with softening behaviour below macroscopic yielding, Materials & Design, 165, (2019), 107573

7) K., Horikawa, S., Cho: Cyclic Hardening Property and Low Cycle Fatigue Behavior of Aluminum Alloys, Transactions of JWRI, 14(2), (1985), 343-349

8) S. Tsutsumi, M. Sano, R. Fincato: Prediction of fatigue crack initiation life of aluminum alloy joints using cyclic elasto-plasticity FEM analysis, Fatigue 2018'MATEC Web of Conferences, 165 (2018), 14012