The Effect of Butt-weld Defects of Aluminum Joints on Fatigue Life Using Basquin Prediction Model

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Abstract

Discontinuities and voids in weldments affect the fatigue life of welded joints. An example of these discontinuities in a welded joint is undercut. The undercut causes high-stress concentrations on the joints that are calculated based on the root radius and depth of the undercut. Therefore, different undercuts cause varying stress concentration increases based on their geometry. Numerous undercut geometries can be found with different levels of effects on fatigue life. Industrial codes and operational standards set conservative tolerances for undercut geometries. Thus, the need for one model that is capable of predicting the fatigue limit for various undercuts is crucial. From this point of view, this paper investigates the capability of the phenomenological Basquin fatigue model for predicting the fatigue life of different undercut geometries. The research is based on a scripted code in VBA using the least square method for calibration and compares the code results to experimental fatigue data. The research results show the good agreement of the Basquin model prediction compared to experimental results.

Keywords - *Fatigue life, Undercut, butt-weld, Basquin model, Notch*

I. INTRODUCTION

This study investigates the fatigue life degradation in a butt-welded joint in industry. Discontinuities in all types of steel pipe welds are observed throughout civil structures and refinery piping. It is crucial for designers to estimate fatigue life degradation and the significance of poor workmanship in welded joints. Many studies have analyzed similar defects in welded joints [1-6] and their effect on fatigue during the service life of the operation. Welded joints are susceptible to accompanying defects such as undercuts (as in Figure 1), voids and misalignment [7].

Extensive work by inspection personnel post welding work, using advanced tools and techniques, are mandatory for discovering weld defects. Design codes and operational standards have suggested some conservative tolerances for all types of weld defects based on an assessment of the fitness of purpose [8-11].

This research will cover the single case of a welding defect called the undercuts in butt-welded joints. The aim of this study is to minimize the tolerance in order to save costs; this approach will benefit the industry without jeopardizing safety regulations and rules [12-14]. The reader is recommended to refer to Refs. [15-17] for further details regarding the problems associated with undercuts in welding.

This research aims to apply the phenomenological model of Basquin [18] to study the effects of undercut in the fatigue life of $1x10^3$ to $1x10^6$ cycles. This region is characterized by very low plastic strain accompanied by elastic strain. It is also a study of a stress-controlled case of fatigue.

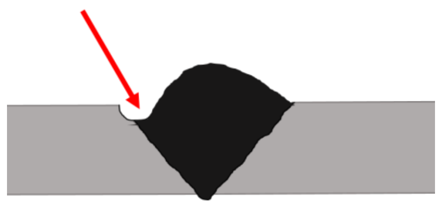

Figure 1: Undercut defect in but-weld.

II. THEORITICAL ANALYSIS

Basquin’s model of life prediction has shown very good results in estimating steel life in high-cycle fatigue (HCF) examples. In equation (5), the Basquin model is described on a log-log scale of a stress-life graph. The stress-life graph is denoted as an S-N curve in many studies. The constants A and B in equation (5) are material constants. This model is based on the stress amplitude of fatigue stress. Another form of the Basquin model is presented in equation (6), with this form being able to be used on a linear-log scale graph [19, 20]. However, the log-log form of the Basquin model in the form of equation (5) is more frequently used in many studies [21].

The undercut effect on the stress amplitude of the fatigue on the fatigue limit can be introduced to the Basquin model by representing a factor that incorporates the defect influence on the fatigue limit. The defect factor is represented in equations (1), (2), (3), and (4) where K_f, K_t, q, a are the fatigue strength reduction factor, stress concentration factor, notch sensitivity, and notch material constant, respectively [22-24]. Interested readers are suggested to refer to Ref. [25] for further explanations of this relation.

$$q = (K_f - 1) / (K_t - 1) \quad (1)$$

$$K_f = 1 + q (K_t - 1) \quad (2)$$

$$q = 1 / (1 + a/\rho) \quad (3)$$

$$\log a = 2.654e^{-7} \sigma_{UTS}^2 - 1.309e^{-3} \sigma_{UTS} + 0.01103 \text{ and } a = 10^{\log a} \text{ in mm} \quad (4)$$

$$\sigma_a = A N_f^B \quad (5)$$

$$\sigma_a = C + D \log N_f \quad (6)$$

III. RESEARCH FOWCHART

This research is based on previous studies' data that were extracted from extensive experimental work by NASA in Ref. [8, 26]. The S-N curve of defected joints was inserted in a log-log graph. The first round of tests was for specimens with zero flaws (K_t = 1), while the other two rounds were for specimens with defected weld joints with different flow geometries (K_t = 2 and K_t = 4). The higher the value of K_t, the more severe the defect is with respect to the fatigue life. All tests were done under zero amount of mean stress. A Visual Basic for Applications (VBA) code is scripted and run with "for loop" strategies performed to find the best fit of the Basquin model to describe the fatigue life degradation due to the undercuts. The calibration is based on the least square regression analysis.

IV. FATIGUE TESTS

The material used was AL 2024-T3 with three different cases. The first test set was for flawless specimens (K_t = 1) that had zero defects. This set of testing provides us with clear results regarding how the material behaves under zero defects on weldments. The other set of tests was for joints with moderate defects on weldments. This set is represented in the Basquin model by K_t = 2. The third and final set of the test scenarios is for specimens with severe defects on weldment that is represented in the model by K_t = 4. The reason for having different undercut sizes is to compare the poorly made weldment joints to the flawless weldments. This difference is very clear in Figure 2, with the red, blue, and green linear lines representing K_t = 1, 2, and 4, respectively. It is obvious that the more the severance of the undercuts (higher K_t), the lesser the fatigue life becomes. All data related to the ductile fracture properties of AL2024-T3 are shown in Table 1

Table 1: Test data summary

Material	AL 2024
Mean stress	Zero
UTS	503 MPa
Yield stress	306 MPa
Flawless specimen	K_t = 1
Moderate undercut	K_t = 2
Severe undercut	K_t = 4

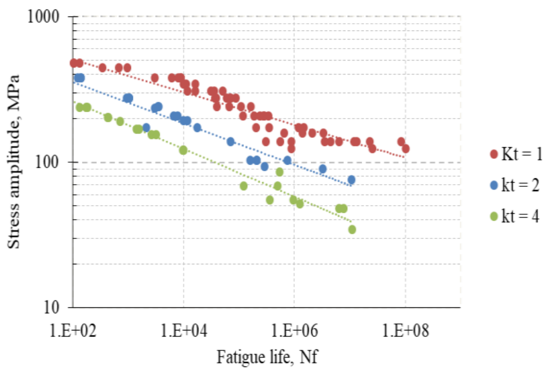

Figure 2: Experimental fatigue life curve of AL 2024-T3 with different undercut geometries [8, 26]

V. CODE AND CALIBRATION

The code was scripted in VBA and run a couple of times to find the best fit of the Basquin model by the least square regression method. The parameters K*f*, *q*, and *a* are all materially and geometrically based. Their values are shown in Table 2. The VBA code was run to ascertain the two parameters A and B in equation (5). After running the code, the optimized values of parameters A and B were determined and are shown in Table 2.

Table 2: Undercut geometrical-based factors and material constants.

Fatigue strength reduction factor, K_f	**1.96 for moderate undercut**	**3.55 for severe undercut**
q	0.968	0.85
a	0.263	
A	2100	
B	-0.19	

VI. RESULTS AND DISCUSSION

The Basquin prediction model shows good agreement with the experimental results. The linear bold lines represent the Basquin model prediction compared to the experimental data. The limitation of this model is that it only predicts the fatigue life in the 10^3 to 10^6 region. All stresses over 10^6 are considered in the endurance limit region where fatigue behaves differently.

The red linear-line represents the original Basquin model with zero effects of undercut (K_t = 1) towards fatigue. It follows the pattern of the experimental fatigue behavior of AL 2024-T3 perfectly, and then starts to fit less well as it approaches 10^7 cycles. Similarly, the green line shows the Basquin model prediction of the fatigue life at K_t = 2. It agrees well with the experimental data, yet shifts off as it gets close to 10^6 cycles. In contrast, the purple line of the Basquin model predicted the fatigue with a severe undercut (K_t = 4) with less accuracy. The life prediction of Basquin model results in Figure 3 show that the prediction becomes more conservative as the K_t increase.

Overall, the research results show that the Basquin model can be used to predict defected weldments of different geometries and level of severity. The values of the least square (R2) show good correlation to the reported laboratory results as in Table 3

Table 3: Least square values for the prediction model of different K_t values.

Stress concentration factor, K_t	Least Square, R^2
1	0.986
2	0.969
4	0.921

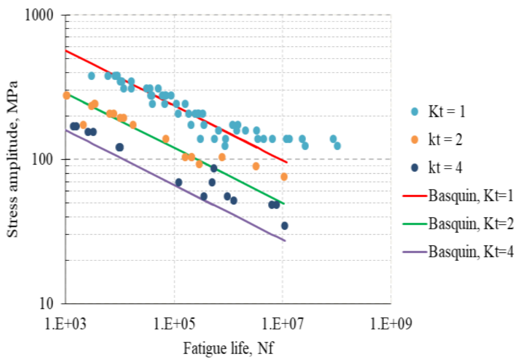

Figure 1: Fatigue life for AL 2024-T3 with different values of K_t.

VII. CONCLUSION

This research study provides a methodology to predict the fatigue life of poor-workmanship welded joints with undercuts of AL 2024-T3. The prediction model used was the phenomenological Basquin model. This model is most often used to predict the fatigue life of sound and flawless joints. This paper extends the application of this model to predict butt-welded joints with undercuts. The experimental fatigue data were extracted from previous studies in Ref. [8, 26]. This study has focused on $1x10^3$ to $1x10^6$ cycles. The undercuts in this study were simulated into two different geometries with K_t = 2 (moderate undercut) and 4 (severe undercut). The VBA scripted code was run using the least square method to determine the material constants A and B in equation **Error! Reference source not found.**. The results in Figure 1 show the good correlation of the Basquin model to experimental results. It is recommended, in future research, to further study the combined effect of the different geometry of discontinuities along with the heat affected zone (HAZ) factors. In conclusion, this study establishes a concise methodology to investigate the effect of poor-workmanship welding quality having undercuts on the fatigue life of Al 2024-T3.

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