FATIGUE DAMAGE ACCUMULATION IN ALUMINUM 7050-T7451 ALLOY SUBJECTED TO BLOCK PROGRAM LOADING: A STUDY COMPARED WITH THE LINEAR DAMAGE RULE

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Abstract. In this paper the fatigue damage accumulation under block program loading is investigated. Alternative flexion bending fatigue tests with a single change in stress amplitude are performed at room temperature for step-down sequence as two-step and three-step loading. The fatigue strength of aluminum 7050-T7451 alloy under block loading is investigated through comparison between the remaining cycles and consumed cycles ratios. The experimental results from the blocks loading fatigue tests are compared with the predictions using Miner's rule. It is shown that, as two-step the fatigue strength is enhanced for smaller consumed fatigue loading and the cumulative fatigue damage calculated in accordance with the LDR , for three-step the fatigue strength occurs to a higher number of consume fatigue loading and the LDR rule trend to underestimate the fatigue life and the accumulative damage becomes higher than unity.

***Keywords**. Block program loading; Fatigue damage accumulation; fatigue loading and aluminum alloy*

1. Introduction

In the field of metallic or light structures (e.g. aircraft structures) the failure of structural components is difficult to assess, particularly when the loading conditions are variable (Pavlou, 2002). The prediction of the fatigue life of the specimens loaded under variable amplitude conditions is a complex subject (Franke, 1999). However, most structural elements are practically subjected to a complex fatigue loading that is accompanied by a change in the stress amplitude. For reliable fatigue designs of components and structures, therefore, it is very important to assess the development of fatigue damage under variable amplitude conditions (Kawai, 2002). Fatigue damage increases with applied load cycles in a cumulative manner which may lead to fracture. Cumulative fatigue damage analysis plays a key role in the life prediction of components and structures subjected to field load histories. In order to predict the life of these components, the damage must be evaluated and a relationship formulated to describe damage accumulation and fatigue life (Fatemi, 1997). The study of damage evolution is an important research aspect of the fatigue failure and safe design criteria. A variety of damage accumulation models have been proposed (Cheng, 1998). For the assessment of fatigue damage under block program loading the most frequently used methodology is the linear damage rule or Miner's linear rule it has received much attention due to its simplicity (Ben-Amoz, 1990).

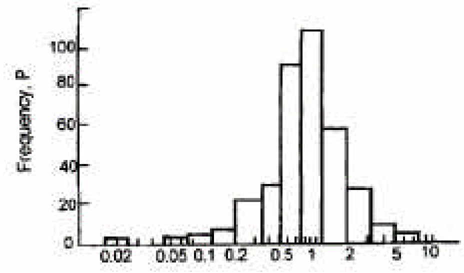
$$\sum_{1}^{s} \frac{n_i}{N_i} = 1 \tag{1}$$

or

$$\sum_{1}^{s} \frac{n_i}{N_i} = D \tag{2}$$

Where s is the number of steps in a block, n_i is the number of load cycles at the stress σ_i , N_i is the number of cycles to a failure under constant amplitude fatigue at the stress σ_I and D is the damage accumulated to the instant of failure (Todinov, 2001). Namely, the fatigue failure occurs when the fatigue damage D has reached unity (D=1). Hence, the fatigue failure criterion for two-step and three-step loading can be described as follow:

$$\frac{n_1}{N_1} + \frac{n_2}{N_2} + \cdots \frac{n_i}{N_i} = 1 \tag{3}$$



Damage (D)

Figure 1. Histograms of the D values distribution.

The equation implies that damage accumulates linearly with applied cycle fraction, independent of life level N_i. When the cumulative damage, calculated by Eq. (2), is less than unity, the process of fatigue damage under block program loading proceeds with a higher intensity than predicted from the linear damage rule, if the cumulative damage sum is more than unity, the process of fatigue damage proceeds less intensively (Troshchenko, 1999). Analysis of the data from experimentally obtained value of D can differ appreciably from unity. The Figure (1) shows a histogram of the distribution of the D, and reveals an appreciable scatter in the D values. The average magnitude of these values is close to unity. This type of analysis assumes that there is no load sequence effect that occurs during the fatigue loading history (Richard, 1997).

The present work aim is to study fatigue damage accumulation under block program loading of step-down sequence as two-step and three-step through the amplitude changes from the blocks loading on the fatigue strength of aluminum alloy 7050-T7451. The experimental results from blocks loading fatigue tests are compared with the predictions using Miner's rule.

2. Material and experimental procedure

2.1 Investigated material

The material used in this investigation was a plate of 7050-T7451 aluminum alloy. The chemical composition is (in wt%): 6.06% Zn, 2.19% Cu, 1.90% Mg, 0.15% Zr, 0.10% Mn, 0.04% Cr, 0.12% Si, 0.14% Fe, 0.06% Ti. The experimental results of the mechanical properties from tensile tests were: elastic modulus 65 GPa , 0.2 yield stress 429 MPa, ultimate tensile strength 502 MPa and elongation 10% in the longitudinal (L) direction. Analysis by light microscopy revealed microstructure of the partially recristallized regions that are large elongated course grains surrounded by finer grains that consist in the equiaxed subgrain population and uniformly distributed fine precipitates of η and η' that lead to precipitation hardening. The design of the flat plate specimens (t=4.0 mm) for all the fatigue tests is shown in Figure (2).

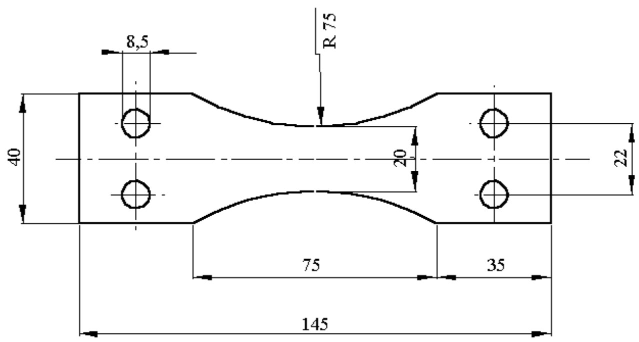


Figure 2. Specimens under study (dimension in mm).

2.2 Experimental procedure

Block program (two-step) and (three-step) loading conditions in fatigue tests with a single change in stress amplitude were performed on the aluminum 7050-T7451 alloy specimens at room temperature. The test procedure is schematically illustrated in Figure (3) (a), (b) and (c). The specimens were first fatigue loaded up to n_1 cycles under a constant stress amplitude σ_1, and then the stress amplitude was changed stepwise to σ_2 and σ_3 as shown in Figure (3), and fatigue loaded until the ultimate failure; the number of cycles to failure under the stress amplitude σ_2, σ_3 is denoted by n_2 and n_3 respectively. Such fatigue tests were performed for block program step-down as two-step: block 1 (σ_1, σ_2;

$\sigma_1 > \sigma_2$), block 2 (σ_1, σ_3; $\sigma_1 > \sigma_3$), block 3 (σ_2, σ_3; $\sigma_2 > \sigma_3$) sequences and three-step; block 4 (σ_1, σ_2, σ_3; $\sigma_1 > \sigma_2 > \sigma_3$) and block 5 ($\sigma_1$, σ_2, σ_3; $\sigma_1 > \sigma_3 < \sigma_2$) alternate sequence. The subscript 1 to blocks 1 and 2 and subscript 2 to block 3 and subscripts 1 and 2 to block4 and subscripts 1 and 3 to block 5 corresponds to the consumed fatigue loading. And subscripts 2 and 3 to blocks 1, 2, 3, 4 and 5 correspond to the remaining fatigue loading as shows the Table (1). The stress level and number of cycles on the block steps were chosen from constant-amplitude fatigue curve (S-N). For blocks fatigue tests, the stress amplitude was changed using several different consumed cycle ratios n_i/N_i; the denominator N_i represents the number of cycles to failure under the constant stress amplitude σ_i. The two blocks program loading to fatigue test were carried out using an alternative flexion bending machine. The stress ratio for consumed and remaining fatigue loading was of R=-1, with a frequency of 25 Hz. In the block fatigue tests the number of specimens were in an average of four. In the case of constant-amplitude fatigue tests the number used to obtained S-N curve is no fewer than 16 specimens.

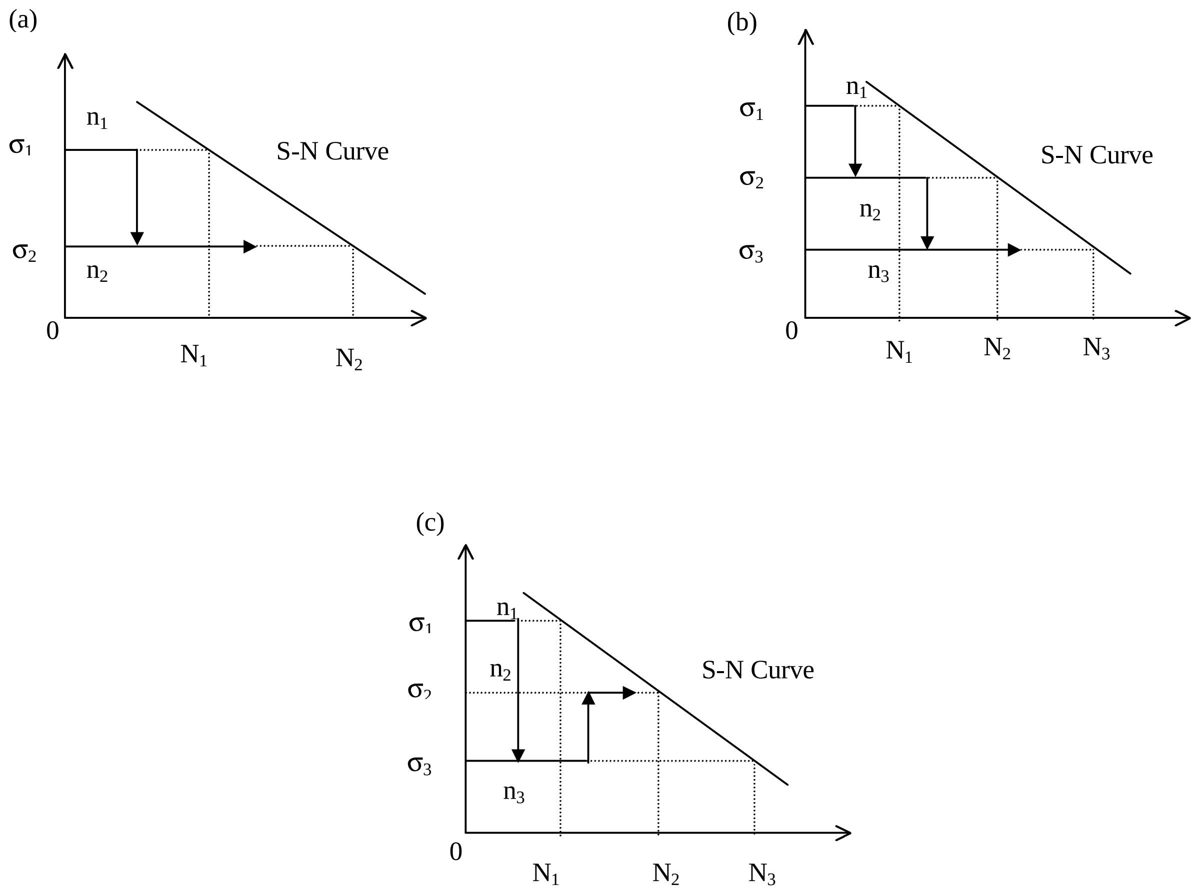


Figure 3. Block program loading. (a) two-step, (b) three-step and (c) three-step alternate.

3. Experimental results

3.1 Block program- fatigue life

The influence of the program loading step-down sequence (H-L) as two-step and three-step through the amplitude change from of the blocks loading on the fatigue strength of aluminum 7050-T7451 alloy can be shown by a simple comparison of the number of cycles to failure n_i for the remaining fatigue at σ_i and N_i for constant amplitude fatigue σ_i from S-N curve, as well as, obtained from the remaining cycles ratio n_L/N_L. On the other hand, the extent of the fatigue damage due to consumed cycles at σ_i is described by the consumed cycle ratio n_H/N_H, when subscripts H an L correspond to the higher and lower amplitudes of two-step and three-step fatigue loading.

Table 1. Characteristic of the block program loading and cumulative damage.

				consumed life	remaining life		cumulative damage
	σ_{1max} (MPa)	σ_{2max} (MPa)	σ_{3max} (MPa)	$n_1(10^3)$	$n_2(10^3)$	$n_3(10^3)$	D (Eq. (2))
Block 1	176	133		2	47		0.846
				2	53		0.943
				4	60		1.126
				4	49		0.959
				13	14		0.731
				20	20		1.069
Block 2	176		85	2		273	1.287
				2		271	1.274
Two				4		173	0.916
step				4		231	1.174
				20		75	1.073
Block 3		133	85		5	101	0.931
					5	198	1.044
					10	229	1.18
					10	239	1.223
					50	166	1.556
				consumed life		remaining life	
Block 4	176	133	85	n_1= 4	n_2= 10	n_3 =172	1.078
				4	10	174	1.084
				4	10	217	1.276
Three				4	10	196	1.184
step				12	10	246	1.698
				12	10	165	1.342
Block 5	176	85	133	n_1= 4	n_3= 47	n_2= 42	1.048
				4	47	55	1.268
				20	47	8	1.082
				4	236	52	2.053

3.2 Block program two-step

The block program-history dependence of the aluminum 7050-T7451 alloy on the fatigue strength behavior through different number of consumed cycles ratio at σ_H on the remaining fatigue life at σ_L is shown in Figure (4). In the case of consumed cycles ratio $n_H/N_H \cong 0.07$, the remaining cycle ratio n_L/N_L is greater than unity for the block 2, while to blocks 1 and 3 are close of unity. This indicates that the remaining fatigue life at the lower amplitude σ_L has been enhanced by the consumed fatigue cycles at the higher stress level σ_H. In the $n_H/N_H \cong 0.15$ the remaining cycle ratio n_L/N_L is greater than unity only to block 3, while to blocks 1 and 2 the values n_L/N_L are around 0.7-1.0. Indicating that the remaining fatigue life at lower stress amplitude also is enhanced. On the other hand, as increase of the consumed fatigue loading the remaining cycle ratio reduces to values around of 0.3. Namely, fatigue life at the lower stress amplitude is reduced by the consumed fatigue cycles at the higher stress level. This observation shows that the remaining fatigue life is more marked for smaller consumed cycle ratio.

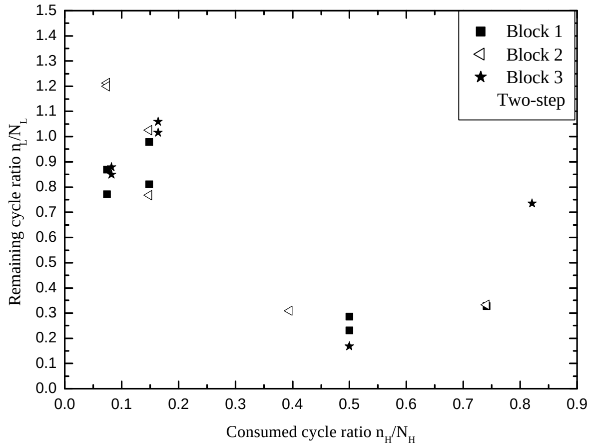


Figure 4. Effects of consumed cycles on the remaining cycle ratios for two-step.

3.3 Block program three-step

The remaining cycles ratio n_L/N_L obtained from the block program loading of three-step of block 4 (σ_1-σ_2-σ_3) and block 5 (σ_1-σ_3-σ_2) are shown in Figure (5). The loading sequence from three-step shows also the dependence of the remaining cycle ratio n_L/N_L on the number of consumed cycle ratio. The remaining cycle ratio becomes smaller as the consumed cycle ratio increase. This observation indicates that the consumed fatigue loading as three-step at higher stress amplitude has also enhanced the fatigue strength of aluminum 7050-T7451 alloy at the lower stress amplitude. The extension of remaining fatigue life occurs for three-step loading as a higher number of consumed cycles than when compared as two-step loading. Consequently, this indicates that the residual fatigue strength of aluminum 7050-T7451 alloy in the three-step loading is very higher when compared as two-step loading.

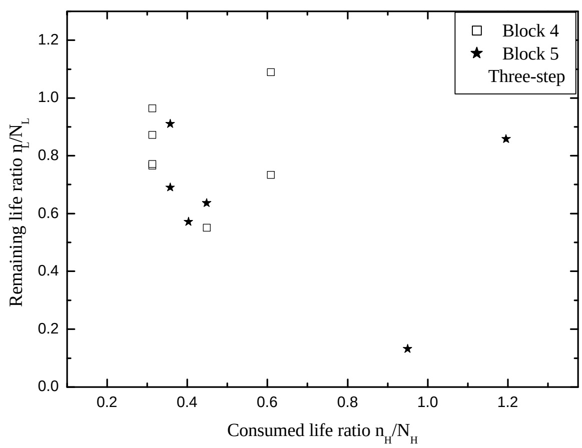


Figure 5. Effects of consumed cycles on the remaining cycle ratios for three-step.

3.4 Fatigue damage under block program loading using Miner’s rule

The assessment of fatigue damage under block program loading is shown in Table (1) The results of the investigation into the fatigue damage accumulation under block program loading are presented in table (1). It follows from Table (1) for aluminum 7050-T7451 alloy tested under two-step and three-step loading, with the stresses and numbers of load cycles on the block step varying over a range, that the accumulated fatigue damage was calculated using Eq. (2). The accumulated damage for two-step loading is close to unity, while for three-step loading the accumulated damage was higher than to unity. Some scatter exists in the data.

A comparison between the fatigue lives observed in the two-step loading and predicted using the Miner’s rule (the LDR rule in short) for the step-down fatigue (H-L) is shown in Figure (6).

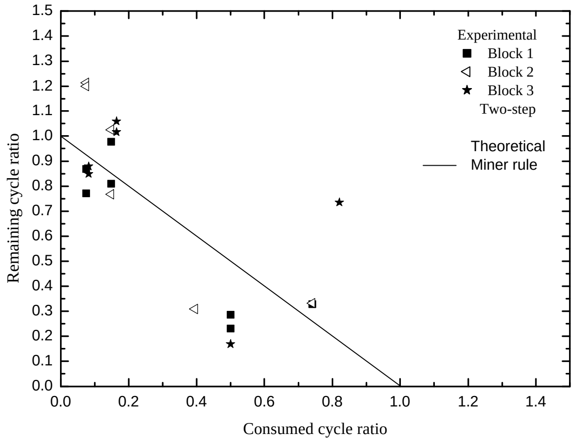


Figure 6. Correlation between theoretical predictions and experimental results for two-step.

The straight solid line in this fatigue damage diagram represents the prediction. As seen in the figure (6), the experimental data for all blocks program loading are distributed in such a way that they intersect with the line predicted using the LDR rule. In this block program loading sequence of two-step, therefore, the LDR rule gives safe predictions for all consumed cycle ratios utilized on the block program. This observation can be confirmed in the Figure (7), which shows the damages accumulated is close to unity and the dependence of the cumulative damage on the ratio between the damages accumulated on the low (d_2) and high (d_1) steps of the block program loading, correspondent the remaining cycle loading and consumed cycle loading, respectively.

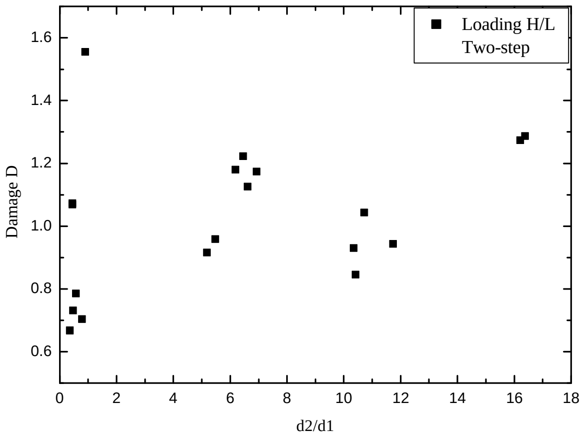


Figure 7. Correlation D versus d_2/d_1 for two-step.

The Figure (8) shows fatigue damage diagrams for block program loading of three-step. In this case the remaining fatigue lives are above of the line predicted of LDR rule to all consumed cycle ratio loading for blocks 4 and 5. Namely, the LDR rule underestimates the values of the three-step fatigue life. Consequently, the summation of the damage on the both steps of the block are higher than to unity. This observation is shown in the Figure (9), when the accumulated damage depends on the relation between the cycles ratio loading, whereas with a decrease in the consumed cycle ratio the cumulative damage has also enhanced.

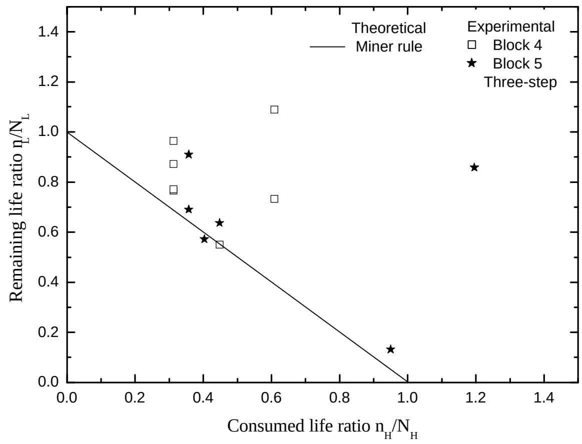


Figure 8. Correlation between theoretical predictions and experimental results for three-step.

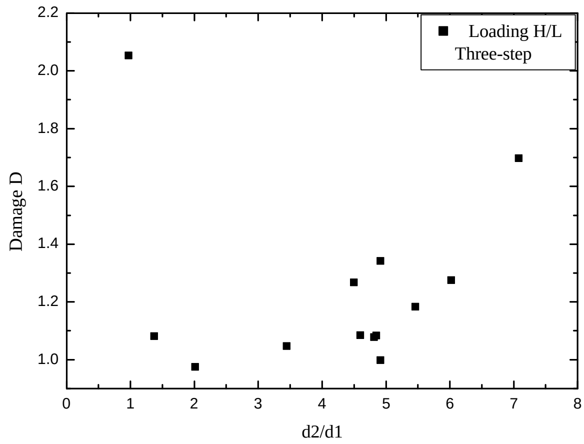


Figure 9. Correlation D versus d_2/d_1 for three-step.

4 Summary and conclusions

The fatigue damage accumulation for block program loading step-down sequence as two-step and three-step through amplitude change on the fatigue strength of aluminum 7050-T7451 alloy was investigated at room temperature under alternative flexion bending cycling conditions. A comparison between the fatigue lives observed in the experimental results and linear damage rule were examined. The results obtained can be summarized as follows:

For block program as two-step the fatigue strength is enhanced for smaller consumed fatigue loading. While for block program as three-step the fatigue strength occurs to a higher number of consume fatigue loading. Consequently, the residual fatigue strength from three-step loading is very higher when compared as two-step loading. This suggests that is attributed to the higher loading interaction for program of three-step.

The experimental results under two-step program loading, the cumulative fatigue damage calculated in accordance with the LDR is close to unity. In the tests under three-step program loading as increase of loading interaction occurs a deviation in the predictions fatigue life. The LDR rule trend underestimates the fatigue life and the accumulative damage becomes higher than unity.

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