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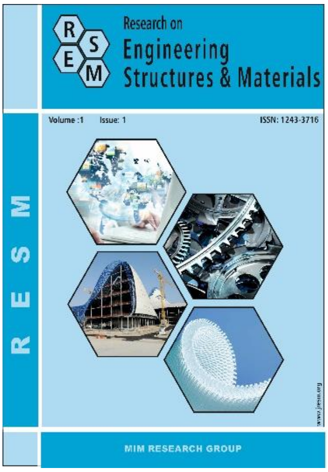

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Research Article

Fatigue-life estimation and material selection for commercial-purity aluminum sheets

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Abstract

This study had two fundamental purposes: fatigue-life estimation by statistical analysis of fatigue test data of cold-rolled commercial-purity aluminum sheets and material selection in HCF and LCF regions. Aluminum alloys 1100 and 1050 were cut in the rolling direction and long transverse direction. The specimens were subjected to cantilever-type plane bending fatigue tests using a fully reversed stress rate at room temperature. A two-parameter Weibull distribution was used for statistical analysis. S–N curves with 12 different reliability levels between 0.01 and 0.99 and empirical formulas were obtained for fatigue-life estimation. The reliability graphs were obtained for material selection.

1. Introduction

Aluminum is a light material with a density (2.7 g/cm^3) that is approximately three times lower than that of materials such as iron, copper, and brass. It shows perfect resistance to corrosion under various environmental conditions such as air, water, and sea, as well as under the action of different chemicals. Furthermore, it possesses attractive characteristics such as esthetic appearance, machinability, and high electric and heat conductivity. It is quite commonly used in the automotive industry and in aircraft owing to its physical, mechanical, and tribological characteristics [1-3]. Aluminum alloys 1100 and 1050 are particularly used for the industry, where high strength is not required but high shaping and corrosion resistances are necessary. They are used to carry chemicals and foods in thin sheet metal works, in tubes and general containers manufactured by deep drawing and spinning processes, in heat exchangers, in welded assemblies, in vehicle plates, and in lighting such as light reflectors [2, 3].

Fatigue is an important parameter in determining the behavior of mechanical parts functioning under variable loads. The fatigue resistance of a structural component is affected by mechanical, metallurgical, and environmental variable factors. Fatigue is the primary reason for 80%–90% of engineering failures. In applications that frequently use aluminum alloys, determining the fatigue performance of the operating element and the effects of the operating parameters on fatigue is necessary. Establishing extensive databases, including stress–life (S–N) information, is very important for precisely evaluating the fatigue characteristics of an element resulting from different operating conditions [1, 3]. Fatigue life is particularly affected by not only the characteristics of a material but also the characteristics of the relevant specimen: microcavities created when an aluminum part is produced, surface flaws, hot or cold deformation, grain size, and changes in the grain structure [3]. The specimens used in this work were cut from commercially-pure AA1100 (99.4% pure) and AA1050 (99.6% pure) sheets. The

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specimens were homogenized at room temperature. The grain sizes of the homogenized AA1100 and AA1050 sheets are 260 and 330 μm, respectively. Effertz, P.S. et al. [4] were conducted to study on the 7050-T76 commercial aluminum sheet. The fine grain size of extruded 7050-T76 aluminum alloy, ranging from 200 to 500 μm. Both this study and theirs have similar main findings. For example, for these three commercially aluminums, the fatigue life decreases with decreasing grain size [5]. Aluminum alloys 1100, 1050 and 7050-T76 should be used in the places where high fatigue level and fatigue strength are not needed. In other words, it is more appropriate to make secure designs of this type of aluminum sheets to work dynamically in LCF region. Also, the fatigue failure criteria were fulfilled for loads of approximately 10-11% of the maximum, suggesting that the material is not recommendable for HCF. For all tested conditions in both studies the coefficient of variation (CV) is low and shape parameter (β) is high, which implies the high repeatability of the fatigue behavior with low scatter.

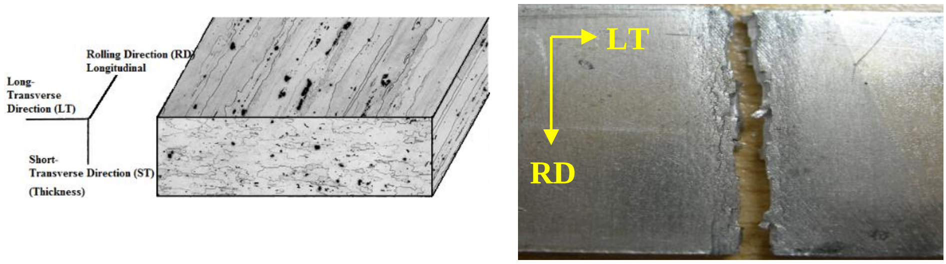
At present, fatigue tests are difficult to conduct due to the influence of many parameters, large number of specimens, long testing time, and test costs. Therefore, fatigue data are very valuable. Using a statistical method to determine mechanical characteristics such as the fatigue life from the data is very important. The S–N curves used to determine the fatigue strength limits of a material are obtained by counting cycles (failure cycle, N) until the material breaks down under the effects of many stress levels (S). These curves are referred to as Wöhler curves or fatigue life diagrams. Scattering may be large in data from tests on aluminum alloys and generally continues until 10^7 or more cycles (high-cycle fatigue) are achieved. The scattering was generally considered to be unimportant in the past since large safety coefficients were used. However, the problems with this variable in mechanical characteristics has gained further importance due to the increase in industrial aluminum use and the rise in costs and improvement of the ground, sea, and aircraft sectors. Precisely estimating the fatigue period of a component operating under dynamic loads before a sudden breakdown occurs has become important. Reliability analysis for these materials has become essential since fatigue data, in particular, show extensive scattering. Therefore, in construction using aluminum, fatigue data must be statistically understood in order to ensure safe application. The commonly used statistical methods are generally related to normal distributions with a mean strength. The Weibull distribution provides more realistic values than other distributions when changes in the life and strength parameters are considered [6-9]. Thus, the literature has shown that the Weibull distribution is advantageous to evaluating the reliability of fatigue data [3, 6-17].

This study had the following aims: (1) statistically evaluate fatigue life data obtained from cantilever-type plane bending fatigue tests applied to 99% commercially pure, general-purpose aluminum sheets produced by cold-rolling; (2) develop S–N curves to estimate the fatigue life of these materials at 12 different reliability levels between R = 0.01 and 0.99; and (3) obtain graphs such as the failure probability and reliability (probability of survival) to help designers in material selection. The two-parameter Weibull distribution was used for statistical analysis of the fatigue life results.

2. Materials and Method

2.1. Aluminum Sheet Specimens

Commercial-purity cold-rolled aluminum sheets were used; Table 1 provides the chemical contents and standard symbols [3, 9, 18-20]. The test specimens were prepared by cutting AA1100 and AA1050 cold-rolled aluminum sheets supplied from the domestic market in Turkey into dimensions of 25 mm × 200 mm × 3 mm in the rolling direction (RD) and long transverse direction (LT) (Fig. 1). These prepared aluminum specimens were subjected to tensile and three-point bending tests according to TS-EN/485-2 and ISO 7438:2005(E), respectively. The test results are presented in Table 2 [3, 9, 18-20] and were consistent with the literature [2, 3, 9, 19-21].



(a) (b)

Fig. 1. (a) Different textures (RD, LT, and ST) and schematic micrograph illustrating grain morphology of aluminum; (b) AA1100 aluminum specimen broken into pieces in long transverse direction (LT)

Table 1. Chemical composition of aluminum sheets (wt%)

Aluminum	Cr	Cu	Fe	Mg	Mn	Ni	Si	Ti	Zn	Al
AA1100	0.002	0.001	0.494	0.005	0.001	0.001	0.098	0.014	0.008	Bal.
AA1050	-	0.006	0.196	0.002	0.117	-	0.065	0.0157	0.004	Bal.

Table 2. Mechanical properties of aluminum sheets

Specimens & Texture	Ult. Tensile Strength (MPa)	Yield Strength (MPa)	Elasticity Module (GPa)	Bending Strength (MPa)	Bending Modulus (GPa)	Hardness (HB)
AA1100 (RD)	126	120	69	120	60	32
AA1100 (LT)	124	118	69	117	54	32
AA1050 (RD)	117	106	69	106	54	30
AA1050 (LT)	113	98	69	103	48	30

2.2. Cantilever-Type Bending Fatigue Tests

Data on the maximum bending strength obtained through the three-point bending tests helped determine the initial strain and stress levels in the S–N curves [3, 6, 9, 18, 22-25]. All tests were performed at room temperature and a stress-ratio of -1.0 (fully reversed). At least 200 materials were broken into pieces to obtain four specimen groups with two different texture structures (RD and LT). Ten strain and stress levels were determined to obtain the S–N curves corresponding to each group. A total of 50 specimens were tested, i.e., five specimens at each of the ten stress levels. Sheet aluminum specimens were tested in deflection-controlled bending fatigue tests. The tests were implemented using cantilever-type device at a 50 Hz frequency that could fix up to four specimens at a time, as shown in Fig. 2. The tests were continued up to 10^7 cycles [3, 6, 9, 19, 20, 23, 24].

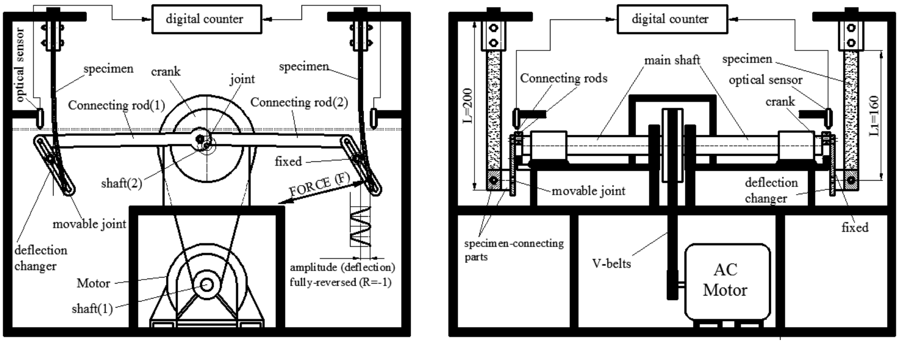


Fig. 2. Schematic of cantilever-type plane-bending fatigue test device: (a) front and (b) side appearance

2.3. Statistical Analysis of Fatigue Life Data

2.3.1. Theory of Weibull distribution

The Weibull distribution is used to model extreme values such as failure times and fatigue life. Two popular forms are the two- and three-parameter Weibull distributions. The probability density function (PDF) of the two-parameter distribution is indicated in Eq. (1). This PDF equation is the most widely known definition of the two-parameter Weibull distribution [4, 6, 7, 9, 26, 27].

$$f(x)=\frac{\beta}{\alpha}\left(\frac{x}{\alpha}\right)^{\beta-1} e^{-\left(\frac{x}{\alpha}\right)^{\beta}} \qquad \alpha\geq 0, \beta\geq 0 \tag{1}$$

where α and β are the scale and shape parameters. The advantages of the two-parameter Weibull distribution are as follows [6, 7, 9]:

- It can be explained with a simple function and easily applied.
- It is frequently used to evaluate the fatigue life of homogeneous, heterogeneous and orthotropic materials
- Its usage is easy based on graphs and simple calculation methods.
- It gives physical rules concerning failure when the slope of the Weibull probability plots is considered.

If the PDF equation is integrated, the cumulative density function (CDF) is obtained, as shown in Eq. (2). Eq. (3) is derived from Eq.(2).

$$F_f(x)=1-e^{-\left(\frac{x}{\alpha}\right)^{\beta}} \tag{2}$$

$$1-F_f(x)=e^{-\left(\frac{x}{\alpha}\right)^{\beta}} \tag{3}$$

$$F_s(x)=1-F_f(x) \tag{4}$$

$$R=1-P \tag{5}$$

In the above equations,

x : variable (usually life); failure cycles in this study (N_f), β : shape parameter or Weibull slope,

α : characteristic life or scale parameter,

$F_f(x)$: probability of failure (P),

$F_s(x)$: probability of survival or reliability (R).

If the natural logarithm of both sides of Eq. (3) is taken, Eq. (6) can be written as follows:

$$\ln\left(\ln\left(\frac{1}{1-F_f(x)}\right)\right)=\beta\ln(x)-\beta\ln\alpha \tag{6}$$

When Eq. (6) is rearranged as a linear equation, the following are obtained: $Y=\ln(\ln(1/(1-F_f(x))))$, $X=\ln(x)$, $m=\beta$, and $c=-\beta(\ln(\alpha))$. Hence, a linear regression model is obtained as shown by Eq. (7):

$$Y=mX+c \tag{7}$$

$$\alpha=e^{(-c/\beta)} \tag{8}$$

The safe design fatigue life can be calculated at a certain value of reliability (R). In case of R=0.368, it is the probability that a part will survive the characteristic strength or characteristic life. This value of reliability can be determined from Eq. 2. In Eq. (2), when $x=\alpha$, the value of R is 0.368

$P=1-e^{-(1)^{\beta}}=1-0.368=0.632$

$P=63.2\%$ is obtained.

According to Eq. (8) and this concept, the characteristic life (α) is the time or number of cycles at which 63.2% of the population is expected to fail. In other words, characteristic life (α) is cycles when approximately 63.2% of specimens have failed. This implies that the characteristic life parameter (N) is fatigue life corresponding to a reliability level of 36.8%. For a critical structural parts, an even higher reliability (probability of survival) should be considered, e.g., R=0.9, 0.99, etc. (P=0.1, 0.01, etc.) [6, 9, 28]. N_R (or N_{1-P}) is value of life indicating x% failure probability and can be calculated from Eq. (9). The median life value (50% survival life=N_{R50}) can be calculated from Eq. (10).

$$N_R=N_{1-P}=\alpha.((-\ln(R_x)^{1/\beta}) \tag{9}$$

$$N_{R50}=N_{1-P50}=\alpha.((\ln 2)^{1/\beta}) \tag{10}$$

The mean life (mean time to failure=MTTF=No), standard deviation (SD), and coefficient of variation (CV) of the two-parameter Weibull distribution were calculated from the following equations [6, 7, 9, 27, 29, 30]:

$$\mathrm{MTTF}=N_o=\alpha.\Gamma(1+1/\beta) \tag{11}$$

$$SD=\alpha.\sqrt{\Gamma(1+2/\beta)-\Gamma^2(1+1/\beta)} \tag{12}$$

$$CV = \frac{SD}{N_o} = \frac{\sqrt{\Gamma(1+2/\beta) - \Gamma^2(1+1/\beta)}}{\Gamma(1+1/\beta)} \quad (13)$$

where (Γ) is a gamma function.

2.3.2. Application of Weibull distribution

Software such as MS Excel and SPSS can be used to draw the Weibull line for X and Y, determine the parameter of Weibull distribution, and perform reliability analysis processes [6, 9, 31, 32]. MS Excel was used in this study. The following processes were carried out to draw Weibull lines and obtain parameters.

1. The number of failure cycle corresponding to each stress was determined successively.
2. A serial number was given to each value (i = 1,2,3,...,n).
3. Each failure probability was used in Bernard's median rank formula, which is given in Eq. (14) [6, 9, 32-34].

$$MR = \frac{i - 0.3}{n + 0.4} \quad (14)$$

where (i) is the failure serial number and (n) is the total test number of samples [6, 32-34].

4. ln(ln(1/(1-MR))) values were calculated for each cycle value (Y-axis).
5. ln(cycle) values were calculated for each cycle value (X-axis).
6. Only the data given for group A samples were transferred to MS Excel. For regression analysis, the Analysis ToolPak add-in was loaded into MS Excel [6, 9, 32].
7. The graphs of ln(cycle) and ln(ln(1/(1-MR))) values were drawn as shown in Fig. 3.
8. The Y=mX+c linear equation given in Eq. (7) was obtained in the most reasonable form from these graphs.
9. β and c were obtained by linear regression (least squares method). The m=β parameter was obtained directly from the slope of the line.
10. α was obtained from Eq. (8)
11. The mean fatigue life corresponding to each stress was calculated from Eq. (11), and the variation coefficients (CV) were calculated from Eq. (13).

The results of the above processes are summarized in Table 3. Fig. 3 gives an example Weibull graph for each stress value. The above processes (1–11) were carried out in order for all sample groups, and the Weibull graphs and parameters α and β were obtained as shown in Table 4.

Table 3 summarizes the results of applying steps 1–11 for each stress level to AA1100 (RD). Fig. 3 presents sample Weibull line graphs for each stress, and Table 4 provides five test results of all specimens, the Weibull mean life, and failure cycles (N_f) for various reliability levels.

Table 3. Summarized Weibull values of AA1100 (RD) specimen

Strain or Deflection (mm)	Stress Amplitude S (MPa)	Cycles (N_f)	Rank	Median Rank (MR)	ln(N_f) (X-axis)	1/(1-MR)	ln(ln(1/(1-MR))) (Y-axis)	Characteristic Life, (α)	Shape Parameter (β)
		996	1	0.129630	6.903747	1.148936	-1.974459		
		998	2	0.314815	6.905753	1.459459	-0.972686		
10.00	105.47	1 065	3	0.500000	6.970730	2.000000	-0.366513	1 083	17.022
		1 068	4	0.685185	6.973543	3.176471	0.144767		
		1 140	5	0.870370	7.038784	7.714286	0.714455		
.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.
		9 634 008	1	0.129630	16.080810	1.148936	-1.974459		
		10 260 000	2	0.314815	16.143763	1.459459	-0.972686		
1.30	13.71	10 562 000	3	0.500000	16.172773	2.000000	-0.366513	11 226 467	10.107
		10 773 000	4	0.685185	16.192554	3.176471	0.144767		
		12 436 750	5	0.870370	16.336166	7.714286	0.714455		

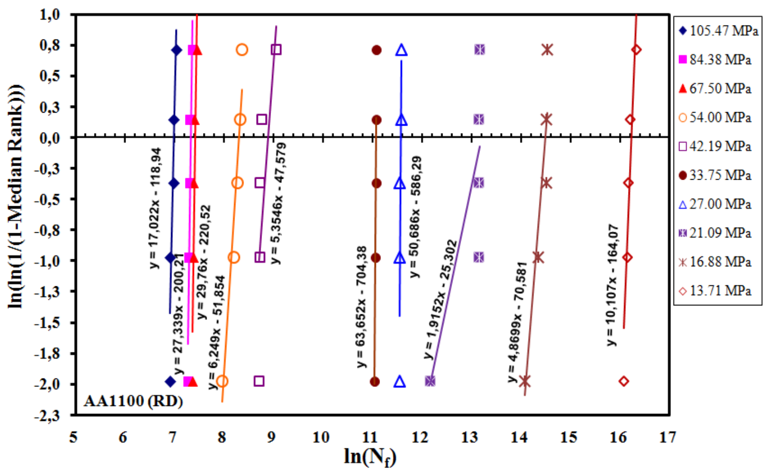


Fig. 3. Weibull lines for AA1100 (RD) specimens

Table 4. Weibull parameters for each stress level and fatigue life (cycles) corresponding to various reliability levels

AA1100 (RD)

Strain (mm)	Stress Amp. (MPa)	test-1 (cycles)	test-2 (cycles)	test-3 (cycles)	test-4 (cycles)	test-5 (cycles)	Alfa (α) (cycles)	Beta (β)	Mean Life (cycles)												
									Reliability or Probability of Survival (R=1-P) →	0.01	0.10	0.20	0.30	0.37	0.40	0.50	0.60	0.70	0.80	0.90	0.99
									Probability of Failure (P) →	0.99	0.90	0.80	0.70	0.63	0.60	0.50	0.40	0.30	0.20	0.10	0.01
										CYCLES											
-	126.00	-	-	-	-	-	1	1.00	1	5	2	2	1	1	1	1	1	0	0	0	0
10.00	105.47	996	998	1 065	1 068	1 140	1 083	17.02	1 050	1 184	1 137	1 114	1 095	1 083	1 077	1 060	1 041	1 019	992	949	826
8.00	84.38	1 425	1 452	1 496	1 502	1 568	1 515	27.34	1 485	1 602	1 562	1 541	1 525	1 515	1 510	1 495	1 478	1 459	1 434	1 395	1 280
6.40	67.50	1 567	1 603	1 612	1 638	1 710	1 652	29.76	1 622	1 739	1 699	1 679	1 663	1 652	1 647	1 632	1 615	1 596	1 571	1 532	1 416
5.12	54.00	2 850	3 603	3 918	4 100	4 275	4 016	6.25	3 734	5 128	4 589	4 334	4 137	4 016	3 960	3 787	3 607	3 405	3 159	2 801	1 923
4.00	42.19	6 000	6 112	6 200	6 413	8 550	7 227	5.35	6 662	9 612	8 445	7 899	7 482	7 227	7 110	6 749	6 375	5 961	5 461	4 747	3 061
3.20	33.75	61 988	63 035	64 118	64 125	64 126	63 964	63.65	63 399	65 517	64 808	64 444	64 151	63 964	63 876	63 597	63 293	62 936	62 474	61 742	59 504
2.56	27.00	102 600	102 893	104 030	106 436	106 875	105 569	50.69	104 407	108 798	107 321	106 565	105 957	105 569	105 387	104 809	104 179	103 444	102 491	100 985	96 410
2.00	21.09	192 375	509 634	512 487	513 000	525 825	546 672	1.92	484 977	1 213 502	845 002	700 877	602 311	546 672	522 279	451 454	384 947	319 114	249 798	168 818	49 495
1.60	16.88	1 282 500	1 689 412	2 003 000	2 010 000	2 052 000	1 969 457	4.87	1 805 536	2 694 881	2 337 357	2 171 629	2 045 976	1 969 457	1 934 418	1 826 674	1 715 704	1 593 708	1 447 380	1 240 680	765 786
1.30	13.71	9 634 008	10 260 000	10 562 000	10 773 000	12 436 750	11 226 467	10.11	10 685 087	13 057 762	12 192 225	11 767 731	11 434 570	11 226 467	11 129 777	10 826 632	10 504 558	10 137 764	9 678 053	8 985 470	7 121 418

AA1100 (LT)

Strain (mm)	Stress Amp. (MPa)	test-1 (cycles)	test-2 (cycles)	test-3 (cycles)	test-4 (cycles)	test-5 (cycles)	Alfa (α) (cycles)	Beta (β)	Mean Life (cycles)												
									Reliability or Probability of Survival (R=1-P) →	0.01	0.10	0.20	0.30	0.37	0.40	0.50	0.60	0.70	0.80	0.90	0.99
									Probability of Failure (P) →	0.99	0.90	0.80	0.70	0.63	0.60	0.50	0.40	0.30	0.20	0.10	0.01
										CYCLES											
-	124.00	-	-	-	-	-	1	1.00	1	5	2	2	1	1	1	1	1	0	0	0	0
10.00	94.92	428	514	643	678	784	668	4.30	608	953	811	746	698	668	655	613	571	526	471	396	229
8.00	75.94	784	1 140	1 148	1 152	1 283	1 200	4.94	1 101	1 636	1 421	1 322	1 246	1 200	1 179	1 115	1 048	974	886	761	473
6.40	60.75	1 636	1 710	1 753	1 782	1 782	1 762	27.92	1 728	1 861	1 816	1 793	1 774	1 762	1 757	1 739	1 721	1 699	1 670	1 626	1 495
5.12	48.60	3 398	3 491	3 633	3 718	3 848	3 701	20.73	3 606	3 984	3 853	3 787	3 734	3 701	3 685	3 636	3 583	3 521	3 442	3 320	2 964
4.00	37.97	6 038	7 756	7 908	7 980	8 550	8 134	7.16	7 618	10 068	9 139	8 693	8 348	8 134	8 035	7 728	7 405	7 043	6 596	5 940	4 277
3.20	30.38	14 250	14 658	16 103	16 509	17 100	16 298	12.82	15 656	18 360	17 394	16 914	16 536	16 298	16 187	15 839	15 466	15 039	14 498	13 674	11 384
2.56	24.30	10 006	26 719	27 075	27 888	36 985	30 773	1.88	27 317	69 408	47 982	39 650	33 970	30 773	29 373	25 316	21 517	17 771	13 843	9 282	2 655
2.00	18.98	94 050	104 062	106 875	110 098	111 150	108 576	14.92	104 830	120 280	114 819	112 095	109 936	108 576	107 942	105 941	103 796	101 326	98 190	93 373	79 765
1.60	15.19	1 682 571	1 689 412	1 702 659	1 710 000	1 795 500	1 742 086	31.98	1 712 282	1 827 291	1 788 114	1 768 202	1 752 227	1 742 086	1 737 331	1 722 236	1 705 878	1 686 826	1 662 269	1 623 719	1 508 698
1.30	12.34	7 965 312	8 721 000	9 112 841	9 205 678	9 234 000	9 115 186	15.69	8 814 385	10 047 327	9 612 990	9 395 978	9 223 701	9 115 186	9 064 523	8 904 661	8 733 062	8 535 340	8 283 898	7 896 901	6 798 220

AA1050 (RD)

Strain (mm)	Stress Amp. (MPa)	test-1 (cycles)	test-2 (cycles)	test-3 (cycles)	test-4 (cycles)	test-5 (cycles)	Alfa (α) (cycles)	Beta (β)	Mean Life (cycles)												
									Reliability or Probability of Survival (R=1-P) →	0.01	0.10	0.20	0.30	0.37	0.40	0.50	0.60	0.70	0.80	0.90	0.99
									Probability of Failure (P) →	0.99	0.90	0.80	0.70	0.63	0.60	0.50	0.40	0.30	0.20	0.10	0.01
										CYCLES											
-	117.00	-	-	-	-	-	1	1.00	1	5	2	2	1	1	1	1	1	0	0	0	0
10.00	94.92	1 645	1 998	2 077	2 222	2 390	2 196	9.03	2 080	2 601	2 409	2 315	2 242	2 196	2 175	2 109	2 039	1 959	1 860	1 712	1 319
8.00	75.94	3 466	4 620	5 528	6 491	7 486	6 145	3.46	5 525	9 557	7 821	7 052	6 484	6 145	5 992	5 527	5 060	4 561	3 982	3 205	1 625
6.40	60.75	8 039	8 811	9 853	10 427	10 649	10 056	8.11	9 476	12 141	11 146	10 664	10 289	10 056	9 948	9 611	9 256	8 855	8 357	7 618	5 701
5.12	48.60	12 497	12 619	13 489	14 040	16 390	14 342	6.23	13 333	18 327	16 397	15 481	14 776	14 342	14 142	13 522	12 876	12 154	11 273	9 993	6 853
4.00	37.97	27 171	29 164	30 476	30 833	32 049	30 815	18.26	29 928	33 503	32 255	31 629	31 130	30 815	30 668	30 203	29 702	29 123	28 385	27 242	23 952
3.20	30.38	42 723	44 257	44 647	44 880	48 593	45 951	14.12	44 287	51 199	48 747	47 526	46 559	45 951	45 667	44 774	43 816	42 716	41 321	39 182	33 176
2.56	24.30	94 350	99 368	102 337	104 114	106 068	103 422	25.82	101 258	109 725	106 818	105 346	104 168	103 422	103 072	101 964	100 766	99 373	97 584	94 789	86 542
2.00	18.98	465 478	498 861	500 487	545 784	591 676	540 583	8.35	510 131	649 101	597 382	572 295	552 738	540 583	534 951	517 363	498 789	477 782	451 679	412 848	311 563
1.60	15.19	1 280 176	1 403 949	1 968 412	2 005 168	2 125 308	1 919 493	3.38	1 723 861	3 016 680	2 457 052	2 209 881	2 027 924	1 919 493	1 870 454	1 722 129	1 573 351	1 414 635	1 231 249	985 977	491 774
1.30	12.34	7 261 948	9 845 908	10 360 059	10 662 578	10 873 874	10 505 159	16.35	10 171 184	11 533 422	11 054 805	10 815 340	10 625 078	10 505 159	10 449 153	10 272 344	10 082 410	9 863 371	9 584 522	9 154 660	7 929 426

AA1050 (LT)

Strain (mm)	Stress Amp. (MPa)	test-1 (cycles)	test-2 (cycles)	test-3 (cycles)	test-4 (cycles)	test-5 (cycles)	Alfa (α) (cycles)	Beta (β)	Mean Life (cycles)												
									Reliability or Probability of Survival (R=1-P) →	0.01	0.10	0.20	0.30	0.37	0.40	0.50	0.60	0.70	0.80	0.90	0.99
									Probability of Failure (P) →	0.99	0.90	0.80	0.70	0.63	0.60	0.50	0.40	0.30	0.20	0.10	0.01
										CYCLES											
-	113.00	-	-	-	-	-	1	1.00	1	5	2	2	1	1	1	1	1	0	0	0	0
10.00	84.38	1 108	1 652	1 963	2 274	2 274	2 079	4.45	1 896	2 929	2 507	2 313	2 167	2 079	2 038	1 915	1 788	1 649	1 485	1 254	740
8.00	67.50	3 070	4 045	6 057	6 082	7 052	5 946	2.76	5 292	10 331	8 040	7 063	6 359	5 946	5 761	5 208	4 663	4 095	3 456	2 635	1 126
6.40	54.00	9 563	11 213	12 589	13 120	13 165	12 669	8.70	11 979	15 099	13 943	13 381	12 942	12 669	12 543	12 147	11 728	11 254	10 664	9 783	7 468
5.12	43.20	14 111	14 765	15 677	18 244	18 765	17 119	5.96	15 876	22 119	19 691	18 542	17 661	17 119	16 870	16 098	15 295	14 400	13 310	11 735	7 912
4.00	33.75	23 278	24 180	27 151	31 322	31 395	28 980	5.43	26 733	38 401	33 796	31 637	29 988	28 980	28 516	27 087	25 605	23 964	21 980	19 140	12 412
3.20	27.00	32 174	32 205	34 668	36 344	41 044	36 549	6.95	34 178	45 527	41 207	39 138	37 538	36 549	36 093	34 673	33 183	31 513	29 457	26 443	18 860
2.56	21.60	51 280	62 896	73 159	76 977	79 211	74 116	6.59	69 113	93 430	84 108	79 662	76 232	74 116	73 140	70 109	66 938	63 390	59 038	52 688	36 895
2.00	16.88	254 786	304 423	314 134	455 301	515 933	405 690	2.56	360 194	735 949	561 631	488 420	436 147	405 690	392 092	351 657	312 195	271 387	226 024	168 677	67 466
1.60	13.50	1 186 864	1 304 576	1 589 473	1 667 932	1 836 201	1 627 214	4.85	1 491 468	2 229 088	1 932 371	1 794 884	1 690 668	1 627 214	1 598 161	1 508 835	1 416 854	1 315 760	1 194 539	1 023 380	630 568
1.30	10.97	3 328 553	6 968 361	9 382 195	10 489 276	10 624 187	9 575 582	3.35	8 596 266	15 101 575	12 280 613	11 036 198	10 120 791	9 575 582	9 329 086	8 583 824	7 836 788	7 040 455	6 121 208	4 893 436	2 427 632

3. Results and Discussion

3.1. S–N Curves

In order to evaluate the fatigue test results, the fatigue strength (stress amplitude) corresponding to 10^7 cycles was taken as the failure criterion [6, 9, 19, 20, 22-25, 35]. Fig. 4 shows S–N curves for the Weibull estimated fatigue life with a reliability of R=0.99. Fig. 5 illustrates R≈0.50 (≈50%) S–N curves for the mean fatigue life data. Eq. (15) was used to evaluate the data from the fatigue tests and is the simplified Basquin function (power function) [3, 6-9, 22-24, 36, 37].

$$S = a.(N_f)^b \tag{15}$$

where S is the stress amplitude (fatigue strength), N_f is the failure cycle causing breakage (fatigue life), and a and b are constants (provided for each specimen in Fig. 4).

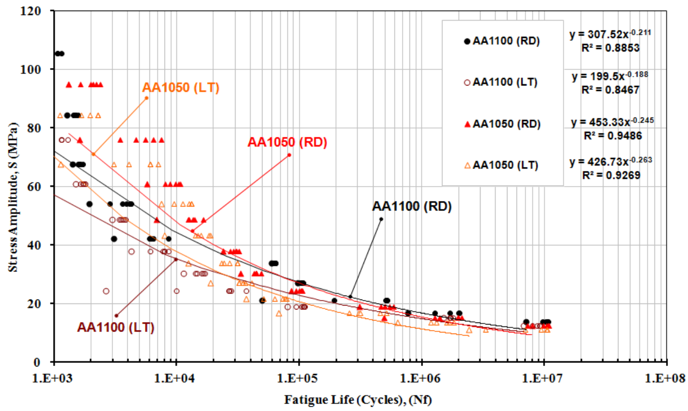


Fig. 4. S–N curves at R=0.99 reliability. R^2=correlation coefficient (0-1).

The correlation coefficients indicate that the Weibull distribution is a good fit.

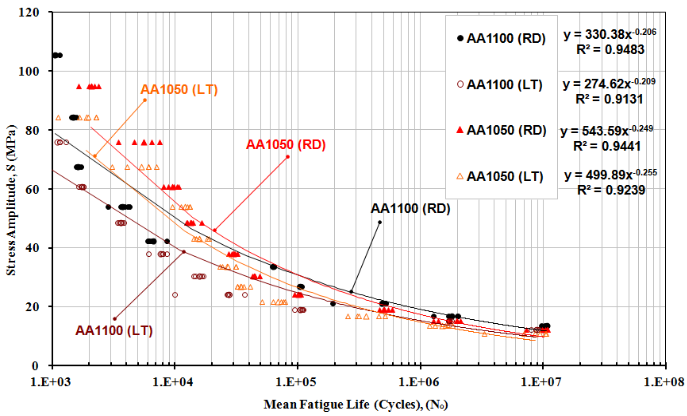


Fig. 5. Mean fatigue life (S–N) curves (reliability level R≈0.50)

In the present study, the S-N curves obtained from AA1050 and AA1100 sheets are generally in accordance with the literature [2, 3, 21, 38-45]. The fatigue resistance of a commercial-pure aluminum sheet is sensitive to a large number of variables. The variables affecting fatigue can be categorized into four types. bulk and geometric factors, and surface- and active loading-related factors. For example, in terms of the geometric factor, small cracks grew faster than large cracks for the same stress intensity range (ΔK). When compared on the basis of ΔK, growth rates in the plate specimens varied from being little different than those in rotating bending specimens to approximately **four times** higher, depending on strain amplitude. Details of this effect and the mechanical properties of some commercial aluminum are given literature in [2, 3, 21, 38-40].

3.2. Scatter of the Fatigue–life Data

The coefficients of variation (CV) corresponding to the mean life (N_o) were calculated using Eq. (13). Figs. 6(a) and (b) show the coefficients of variation (CV) and shape parameter (β), respectively, versus N_o curves. These curves were observed for different specimen groups and play an important role in aluminum design and application [6, 7, 9]. A high coefficient of variation (CV) indicates a great deal of data scattering, while a high shape parameter (β) indicates less scattering.

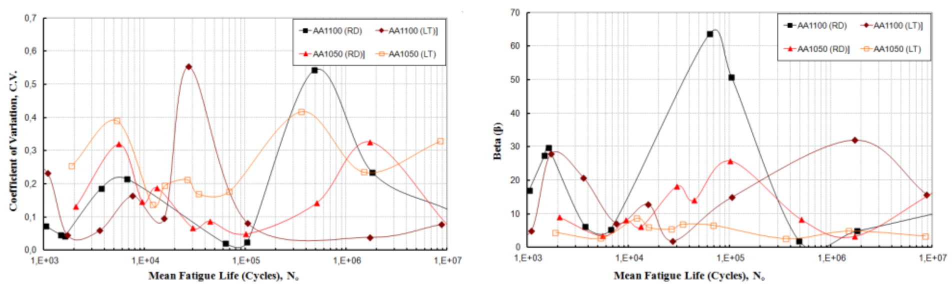


Fig. 6. (a) Coefficient of variation (CV); (b) relationship between shape parameter (β) and mean fatigue life (N_o)

3.3. Reliability Analysis of Fatigue Tests and Boundaries of S–N Curves

The fatigue life results based on the texture structure (RD and LT) of the aluminum sheets showed scattering. Safe life and reliability are important parameters for construction design using aluminum sheets. In engineering, the term "reliability" refers to the probability that a product or system will perform its designed functions under a given set of operating conditions for a specific period of time. It is also known as the "probability of survival" [6, 7, 9, 46]. Fig. 7 and 8 explain the term "reliability" in engineering. Fig. 7 shows the S–N curves corresponding to various reliability levels of the specimens. The best-fit equations relevant to the graphs were obtained to provide the **a** and **b** coefficients of the power function. The failure cycle (fatigue life) can be calculated with respect to a desired stress (according to the required reliability level). In an alternative method, a vertical axis is drawn from the X axis with respect to the desired cycle to coincide with the graph and stress at the required reliability level. As shown in Fig. 7, S–N curves with 12 different reliability levels between 0.01 and 0.99 and empirical formulas were drawn for fatigue-life estimation. These S-N curves can be good guide for engineers.

3.4. Material Selection from AA1100 and AA1050 or RD and LT

Fig. 8 shows the reliability or probability of survival graphs corresponding to the aluminum sheets used in this study in low cycle fatigue (LCF) regions (10^4–10^5) and high cycle fatigue (HCF) regions (10^6–10^7). These graphs were obtained using Eqs. (3) and (4).

For example, any horizontal axis may be drawn from the Y axis at any "reliability" such as 99% or 50% to coincide with the graph and determine the stress value corresponding to that probability of the specimen. This stress value can then be converted to cycles using the curve equations provided in Fig. 7. The most important characteristic of the graphs provided in Fig. 8 is that they facilitate material selection from AA1100 and AA1050 or RD and LT. For example, if we consider the graphs corresponding to $N=10^4$ and $N=10^5$ cycles (Figs. 8a and b), AA1050 (RD) is preferred in the LCF region. However, in the HCF regions of $N=10^6$ and $N=10^7$, AA1100 (RD) is preferred. As another example, AA1100 (LT) is preferred rather than AA1050 (LT) at R=0.50 (50%) reliability level in the HCF region (Fig. 8c) corresponding to $N=10^6$ cycles.

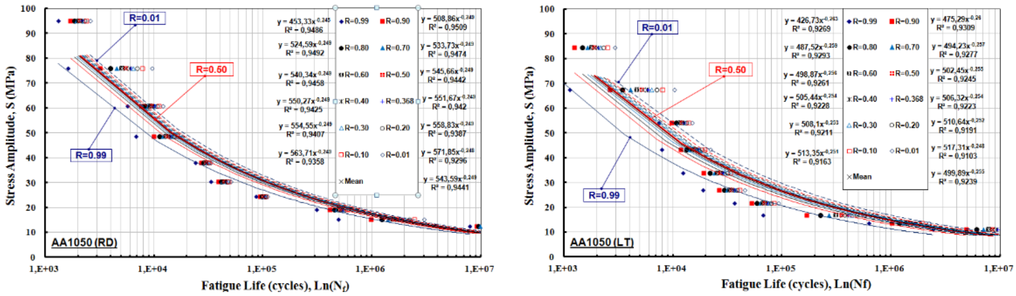


Fig. 7. S–N curves for various reliability levels

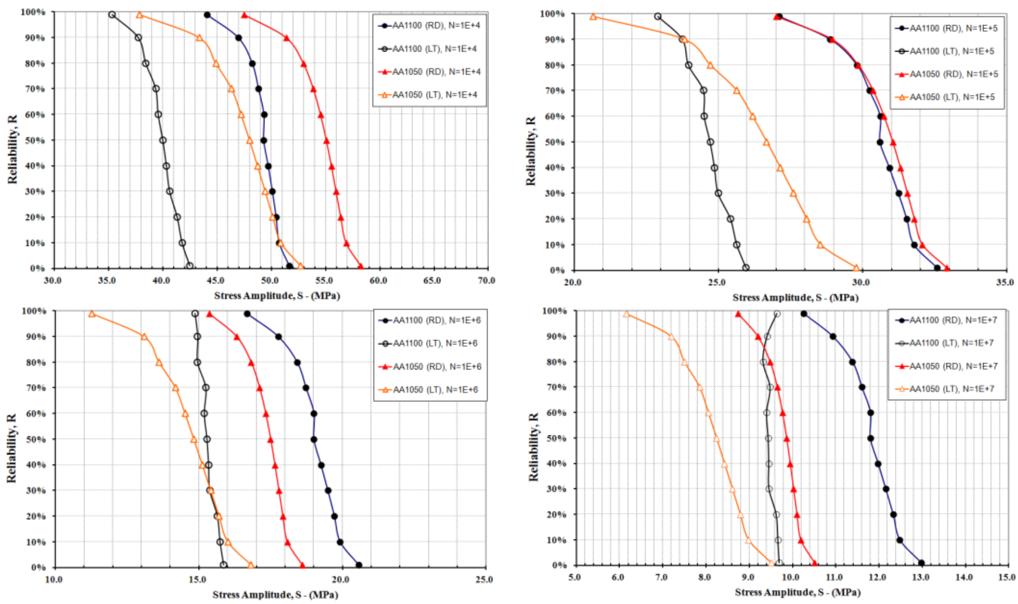


Fig. 8. Reliability (probability of survival) graphs for LCF and HCF regions

3.5. Calculating Guaranteed Period

As an example, AA1050 (RD) aluminum plate was used in a building platform and subjected to 250 cycles under an average stress of 15 MPa (in the 10^6 region) every day. In order to calculate the guaranteed period corresponding to a R=0.99 reliability level, Table

4 shows that 491774 cycles take place at R=0.99 reliability for an average stress value of ≈15 MPa.

Thus, the following calculation can be implemented:

$$\frac{491774 \text{ cycles}}{250 \dfrac{\text{cycles}}{\text{day}} x365 \dfrac{\text{days}}{\text{year}}} = 5.38 \text{ year}$$

3.6. Results

Variations in fatigue life values of the aluminum specimens were modeled using the Weibull distribution. Ultimately, the results can be confidently used to help consumers make proper material selections. The following results were obtained in this study:

- As shown in Figs. 4 and 8, for the same reliability levels, the AA1050 (RD) specimens provided the longest fatigue life at the LCF region of 10^4–10^5 cycles, and the AA1100 (LT) specimens provided the shortest fatigue life. However, at the HCF region of 10^6–10^7 cycles, the AA1100 (RD) specimens provided the longest fatigue life, and the AA1050 (LT) specimens provided the shortest fatigue life.
- Table 4 provides the test results of all specimens and their failure cycles at 12 different reliability levels between 0.01 and 0.99. The α and β parameters calculated for each stress value and the mean life values are also provided. The guaranteed period corresponding to each reliability level indicated in Table 4 can be calculated.
- Figs. 4 and 5 provide the S–N curves of all specimens at reliability levels of R=0.99 and R≈0.50 (mean fatigue life), respectively, and the corresponding power function parameters were obtained. The fatigue life of the relevant machine component under any stress can be calculated using these graphs. The S–N curves with reliability levels of R=0.90 or more must be used for designs where reliability and safety are of high priority, such as aircraft.
- As shown in Fig. 6a, the AA1100 (RD) specimens showed the largest scattering at 10^5–10^6 cycles, and the AA1100 (LT) specimens showed the greatest scattering at 10^4–10^5 cycles. As shown in Fig. 6b, the shape parameter (β) corresponding to AA1100 (RD) has reached its largest value at approximately 10^5 cycles. As shown in Table 4, the mean number of cycles varied between N_o=104407 and 63399, and the shape parameter varied between β=50.69 and 63.65. This indicates that scattering was the least under this condition. The shape parameter (β=1.878) reached its lowest value when N_o=27317 cycles for the AA1100 (LT) specimen. Therefore, scattering was the most under this condition.
- Safe and reliable design life is particularly important for machine components operating under dynamic loads. S–N curves with 12 different reliability values are drawn in Fig. 7 and presented for the benefit of designers. These curves may also be considered as reliability or safety limits to determine the time at which an element under any stress amplitude will show its first failure. These curves can help designers to reliably estimate the required fatigue life values in advance.
- As shown in Table 4, the mean cycle values calculated using the Weibull distribution were very close to the cycle values with a reliability of R=0.50. The Weibull mean values of the distributed fatigue data may also be accepted as the

"fatigue life with 50% reliability". The S–N curves and power function parameters corresponding to R≈0.50 are provided in Fig. 5.

- Reliability (probability of survival) graphs for $N=10^4$, $N=10^5$, $N=10^6$ and $N=10^7$ cycle regions are provided in Fig. 8. The reliability percentage with respect to stress or fatigue life for any reliability level can be easily determined and compared by using these graphs. These graphs will help designers in material selection.
- When the actual test results are very similar, the appropriate material may be selected by using the reliability (probability of survival) graphs shown in Fig. 8. For example, the AA1100 (RD) and the AA1050 (RD) materials show very similar test results when $N=10^5$ cycles; based on Fig. 8b, AA1050 (RD) is preferred.
- As shown in this study, obtaining S–N curves at different reliability levels using the two-parameter Weibull distribution is extremely practical. Another advantage is that these distribution parameters can be calculated by functions available in MS Excel and other software.

4. Conclusions

According to this study, the two-parameter Weibull distribution is a suitable method for evaluating the fatigue life data obtained from fatigue tests of aluminum sheets. S–N curves with different reliability levels between 0.01 and 0.99 and empirical formulas were obtained for fatigue-life estimation. These S-N curves and reliability graphs can be good guide for engineers. This study realized the applicative importance of the numeric values obtained from fatigue tests of the aluminum materials intended for use in construction. When the data scattering (distribution) is large, the most appropriate step is to use data according to the reliability percentage determined with respect to the point of use instead of the arithmetic mean value of the acquired data. For example, if the aluminum material is meant to be used in aircraft or tankers carrying chemicals, reliability values of 90% or more are required; if the material is meant to be used in clothes hangers with no vital importance, reliability values of 50% can be used. Also, a method is introduced here in which the decision-making problem associated with replacement and reliability based on fatigue failure of aluminum sheets. According to the test results, aluminum alloys 1100 and 1050 should be used in the places where high fatigue level and fatigue strength are not needed. In other words, it is more appropriate to make secure designs of this type of aluminum sheets to work dynamically in LCF region.

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