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Reliability assessment and prediction of a fatigue design criterion for the gas-welded joints †

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Abstract

Gas metal arc welding is a very important and useful technology in the fabrication of railroad cars and commercial vehicle structures. However, since the fatigue strength of the joints welded by gas metal arc welding is considerably lower than that of the parent material due to stress concentration and metallurgical changes at the weld, the fatigue-strength assessment of welded joints is very important for the reliability and durability of railroad cars and the establishment of a criterion for long-life fatigue design. In this paper, in order to save time and cost for the fatigue design, an accelerated life-prediction method that is based on the theory of statistical reliability was investigated. Its usefulness was verified by comparing the $(\Delta\sigma_a)_R$-N_f relationship that was obtained from actual fatigue test results with the $(\Delta\sigma_a)_R$-$(N_f)_{ALP}$ relationship that was derived from accelerated life testing. And the reliability of the predicted life was evaluated. The reliability of the accelerated life-prediction on the base of actual test data was analyzed to be 80% for the plug-type gas-welded joints and 95% for the ring-type gas-welded joints.

Keywords: Gas metal arc welding (gas welding); Gas welded joint; Welding residual stress; Fatigue strength; Fatigue design; Reliability; Accelerated life prediction; Theory of statistical reliability

1. Introduction

Typical railroad-car and commercial vehicle body structures consist of a side frame, roof frame, under-frame, and end-frame; these frames are fabricated and combined through gas metal arc welding and electric-resistance spot-welding technologies with various thin, pressed sheets [1]. As is well known, the weld that arises from gas metal arc welding technology is a source of not only stress concentration but also changes in composition and metallurgy that are caused by the input of heat in the process of gas metal arc welding. Therefore, the fatigue strength of gas-welded joints is considerably lower than that of the parent material. Thus, the fatigue strength of a gas-welded joint affects the rigidity and durability of the gas-welded structure. In the design process for gas-welded thin-sheet structures, such as railroad cars and commercial vehicles, first of all, it is necessary to secure information on the influence of geometrical factors on the fatigue strength of welded joint. With regard to the fatigue design of gas-welded thin-sheet structures, designers and researchers have so far tried to determine the criteria for fatigue design by using either the relationship between the fatigue-load range (ΔP) and the fatigue life (N_f) or the relationship between the stress ($\Delta\sigma$) and the fatigue life (N_f) [2-4].

It is difficult to find out the statistical approaches to improve the reliability of fatigue data and to determine the criteria for fatigue design. In fact, in spite of the tester's effort, the reliability of fatigue data can be reduced due to the influence of many factors, such as the variation of test conditions, sampling errors of materials, tester's skills, etc., in the process of long-term fatigue tests.

Therefore, in this paper, in order to save time and cost for fatigue design, an accelerated life-prediction method that is based on the theory of statistical reliability is investigated. And the reliability of the predicted fatigue design data was evaluated. Its usefulness is verified by comparing the $(\Delta\sigma_a)$ - N_f relationship that is obtained from the actual results of long-term fatigue tests with the accelerated $(\Delta\sigma_a)_R$-$(N_f)_{ALP}$ relationship. The flow of this research mentioned above is as shown in Fig. 1.

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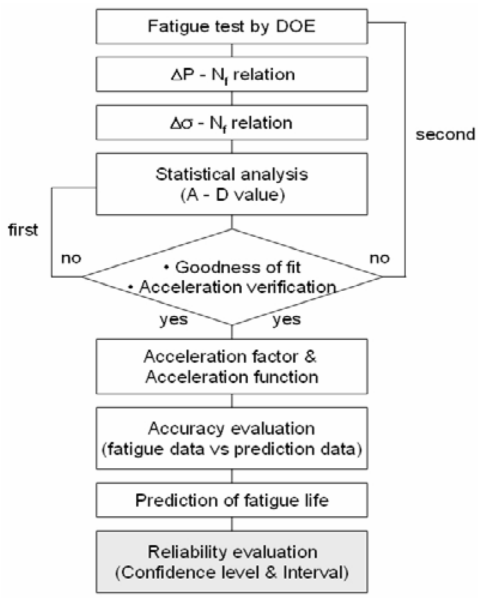


Fig. 1. Flow of fatigue life prediction and reliability evaluation (DOE: design of experiment, A-D: Anderson-Darling).

2. Accelerated life prediction method

2.1 Verification of goodness of fit

The verification of goodness of fit for the distribution of fatigue life data consists of two steps. The first step is to verify that the obtained fatigue data can make fit to which life distribution. The criterion of verification is based on either the A-D statistical value, or P-value. The A-D statistical value implies a magnitude of the difference between the lognormal cumulative distribution function as plotted on a probability sheet and the theoretical distribution function. It is determined by calculating the square of the distance between the straight line and the plotted point [5]. Therefore, with regard to the choice of a proper distribution for the life data, among the distributions being considered, a distribution that has the least A-D statistical value should be chosen as the appropriate statistical model. Table 1 illustrates A-D statistical value on the fatigue life data of plug- and ring-type gas- welded joints that are used as the typical types of gas-welded joint in the railroad-car and commercial vehicle body structures. Figs. 2-3 show the $(\Delta\sigma_a)_R$-N_f relations taking the welding residual stresses into account [6]. In Table 1, the case having the least A-D statistical value among the four distribution models of Table 1 means the most proper distribution model [7].

The second step is to analysis a relationship with a bathtub curve, as shown in Fig. 4. Fig. 4 is divided into three sections: decreasing failure rate (DFR) in the early life; constant failure rate (CFR) that represents a comparatively low and constant rate of failure; and increasing failure rate (IFR) in the later life. Since this paper is related to the fatigue life of materials, the reliability of the accelerated life test must be analysed in the IFR section. Table 2 illustrates applicable distribution model and type of failure for plug- and ring-type gas-welded joints.

Table 1. Result of A-D value for specimen of plug- and ring-type gas-welded joints.

Welded joint type (plate thickness)		Four ways probability			
		Anderson-Darling value			
		Weibull	Lognormal	Exponential	Normal
Plug	ST(1.5)+ST(1.5)	2.126	2.126	3.328	2.222
	ST(1.5)+HT(1.5)	2.156	2.202	3.230	2.168
	ST(1.5)+DLT(1.5)	2.133	2.154	3.106	2.143
Ring	ST(1.5)+ST(1.5)	2.119	2.150	3.240	2.136
	ST(1.5)+HT(1.5)	2.107	2.139	3.293	2.111
	ST(1.5)+DLT(1.5)	2.101	2.136	3.139	2.114

LT: Low tensile HT: High tensile
ST: Special tensile DLT: Deadlite tensile

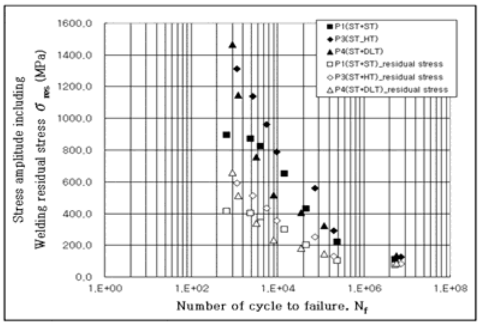


Fig. 2. $(\Delta\sigma_a)_R$-N_f relation of the plug-type gas- welded joints.

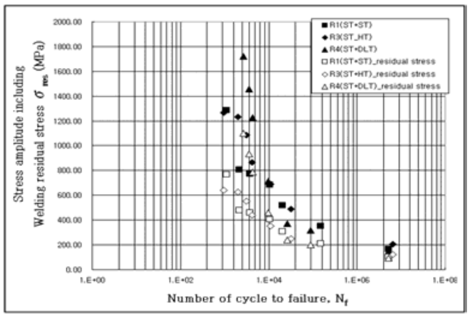
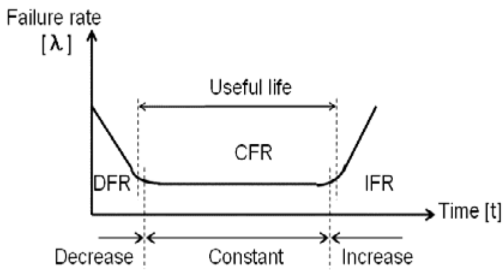


Fig. 3. $(\Delta\sigma_a)_R$-N_f relation of the ring-type gas- welded joints.



DFR : σ > 0.8 , m< 1, CFR : σ = 0.5 , m = 1 / IFR : σ < 0.2 , m > 1 (σ ; scale parameter , m ; shape parameter)

Fig. 4. Bath-tube curve.

Table 2. Applicable distribution model and type of failure for plug- and ring-type gas-welded joints.

Welded joint type (plate thickness)		Fitting distribution model	A-D value	Shape/Scale parameter	Failure type
Plug	ST(1.5)+ST(1.5)	Lognormal	2.126	0.12	IFR
	ST(1.5)+HT(1.5)	Weibull	2.156	7.95	IFR
	ST(1.5)+DLT(1.5)	Weibull	2.133	6.38	IFR
Ring	ST(1.5)+ST(1.5)	Weibull	2.119	10.73	IFR
	ST(1.5)+HT(1.5)	Weibull	2.107	8.27	IFR
	ST(1.5)+DLT(1.5)	Weibull	2.101	4.90	IFR

As illustrated in Table 2, a ST(1.5)+HT(1.5) gas-welded joint of the plug- type was analysed to be applicable to the log-normal distribution. Further, both the ST(1.5)+HT(1.5) and the ST(1.5)+ DLT(1.5) gas-welded joints of the plug-type and the ring-type, respectively, were applicable to the Weibull distribution. All failure-rate analyses of the joints were performed in the IFR regime.

2.2 Verification of acceleration

Acceleration presents a correlation analysis between the life data tested in the accelerated condition. When plotted the life data on the probability sheet, if the regression lines on the accelerated conditions will be parallel in each other, then it is possible to decide that acceleration between the two conditions is verified [8]. In the case of the Weibull distribution, the slope of the regression line corresponds to the shape parameter, and in the case of the lognormal distribution, the slope of the regression line corresponds to the scale parameter. A means of testing the above acceleration is to verify the similarities in the slope of the regression line applied to the same probability sheet as Weibull probability sheet. If the similarities are confirmed without excessive differences, the acceleration goodness-of-fit is deemed to have been accomplished. As the examples, Figs. 5 and 6 illustrate the results of acceleration verification for the Weibull distribution of the plug- and ring-type gas-welded joints. Since both of their relationship between the accelerated maximum tensile load and fatigue life are analysed as the all regression lines are parallel in 95% reliability, and 5% significance level, their acceleration goodness-of-fits are deemed to have been accomplished.

2.3 Acceleration model

The acceleration model is a chemical and physical model that mathematically represents the relationship between the stress and the life. Since this model presents the parameters (mean and standard deviation) of the life distribution as functions of the stress variables, the model is very important for analyse the data of the accelerated life test. Since this study focuses on an accelerated model of metal fatigue that arises from mechanical loading, the inverse-power model [9] was

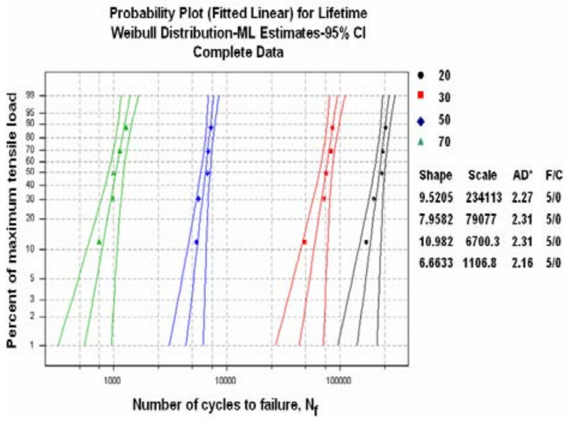


Fig. 5. Acceleration verification of plug-type gas-welded joints (ST(1.5)+ST(1.5)).

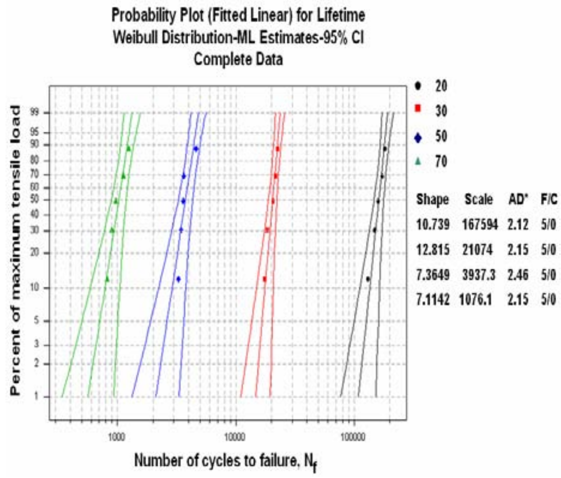


Fig. 6. Acceleration verification of ring-type gas-welded joint (ST(1.5)+ST(1.5)).

applied. This model can be represented via a typical formula, as follows:

$$\tau(V) = \frac{A}{V^{\gamma}} \quad (1)$$

where A, γ : constants, τ (v): lifetime, V: stress value.

Taking logarithm on both sides, then

$$\ln \tau(v) = \ln A - \gamma \ln V = A' - \gamma \ln V. \quad (2)$$

Table 3 illustrates the acceleration function for the plug- and ring-type gas-welded joints. The accelerated condition was assumed as being 30%, 50%, and 70% of the maximum tensile strength under the fatigue limit of 10^7 cycles. MINITAB 14.0 was the commercial package used in statistical data analysis.

Table 3. Acceleration function and R-square value of plug- and ring-type gas-welded joints.

Welding Type	Specimen	A.F. (Acceleration Function)	R-square
Plug	ST(1.5)+ST(1.5)	$y = 3E+11X^{-4.6007}$	97.25%
	ST(1.5)+HT(1.5)	$y = 1E+11X^{-4.2565}$	97.25%
	ST(1.5)+DLT(1.5)	$y = 1E+10X^{-3.7548}$	97.25%
Ring	ST(1.5)+ST(1.5)	$y = 2E+10X^{-3.9349}$	97.25%
	ST(1.5)+HT(1.5)	$y = 2E+08X^{-2.8376}$	97.25%
	ST(1.5)+DLT(1.5)	$y = 3E+08X^{-2.7124}$	97.25%

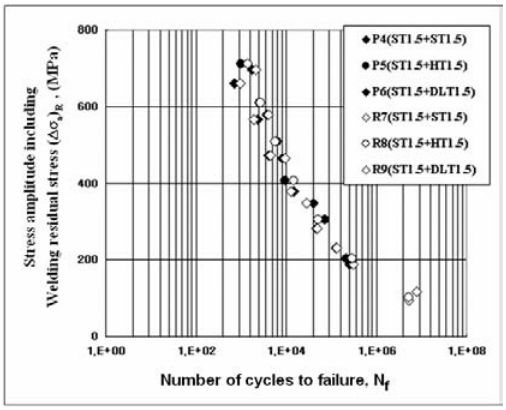


Fig. 7. Comparison of $(\Delta\sigma_a)_R$-N_f and $(\Delta\sigma_a)_R$-$(N_f)_{ALP}$ for plug-type gas-welded joints.

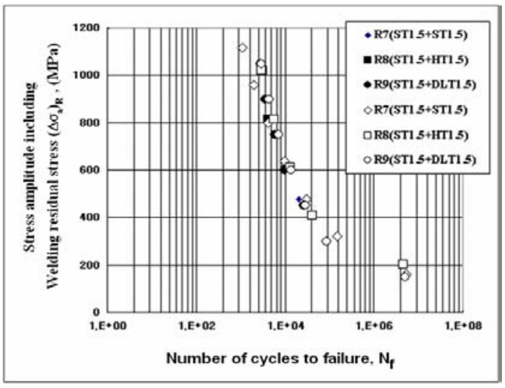


Fig. 8. Comparison of $(\Delta\sigma_a)_R$-N_f and $(\Delta\sigma_a)_R$-$(N_f)_{ALP}$ for ring-type gas-welded joints.

3. Accelerated life prediction of the gas-welded joints

Figs. 7 and 8 show the comparison of $(\Delta\sigma a)_R$-N_f and $(\Delta\sigma a)_R$-$(N_f)_{ALP}$ for the ring- and plug-type gas-welded joints. The accelerated lives in Tables 4 and 5 were predicted by using the acceleration functions illustrated in Table 3, which were determined from statistical analyses through the acceleration model mentioned in section 2. From the result of the accelerated life prediction through the actual fatigue-test data of the plug-type gas-welded joint; ST(1.5)+ST(1.5), ST(1.5)+HT(1.5), and ST(1.5)+DLT(1.5), the mean accuracy of the accelerated life prediction was assessed to be (81~86)% of the actual test life. Under the assumption that the fatigue limit for the infinite life was the normal condition, the predicted life at 20% of the maximum stress amplitude including welding residual stress was analysed as having been accelerated by a factor of 24 (ST(1.5)+ST(1.5)), 19 (ST(1.5)+HT(1.5)), and 13 (ST(1.5)+DLT(1.5)) when compared to the actual test life. In the case of the ring-type gas welded joint, the mean accuracy of the predicted life was estimated to be (96~97)% of the actual test life and accelerated by a factor of 15 (ST(1.5)+ST(1.5)), 7 (ST(1.5)+HT(1.5)), and 7 (ST(1.5)+DLT(1.5)) under 20% the maximum stress amplitude including welding residual stress. From Figs. 7 and 8, it can be seen that the actual test data and the predicted data accord well with each other. Therefore, it is expected that the results of the analysis will provide a useful method to determine the criterion for fatigue design and predicting a specific target life in the region of short lives and high stresses.

Table 4. Accuracy assessment of accelerated life prediction for plug-type gas-welded joints.

Condition of the specimens for plug welded joint		Percentage Of maximum stress amplitude Including welding residual stress					Remark
Specimen	Items	70%	50%	30%	20%	10%	
ST(1.5) + ST(1.5)	Fatigue test (N_f)	709	4,074	46,965	251,761	5,417,206	
	A.L.P.(N_f)	974	4,578	48,010	310,079	-	
	A.F.	7,728	1,643	157	24	1	
	Accuracy	73%	89%	98%	81%	-	85%
ST(1.5) + HT(1.5)	Fatigue test (N_f)	1,031	6,381	73,978	221,330	5,304,080	
	A.L.P.(N_f)	1,401	5,866	51,598	289,845	-	
	A.F.	3,955	944	107	19	1	
	Accuracy	74%	92%	70%	76%	-	79%
ST(1.5) + DLT(1.5)	Fatigue test (N_f)	1054	3714	40292	125646	7829296	
	A.L.P.(N_f)	1180	4175	28425	130284	-	
	A.F.	1490	421	62	13	1	
	Accuracy	89%	89%	71%	96%	-	85%

A.L.P. : Acceleration Lifetime Prediction
A.F. : Acceleration Factor

Table 5. Accuracy assessment of accelerated life prediction for ring-type gas-welded joints.

Condition of the specimens for ring welded joint		Percentage Of maximum stress amplitude Including welding residual stress					Remark
Specimen	Items	70%	50%	30%	20%	10%	
ST(1.5) + ST(1.5)	Fatigue test (N_f)	1,008	3,714	20,217	159,710	5,256,817	
	A.L.P.(N_f)	1,098	4,128	30,811	151,917	-	
	A.F.	2,115	563	75	15	1	
	Accuracy	92%	90%	66%	95%	-	88%
ST(1.5) + HT(1.5)	Fatigue test (N_f)	1,067	3,146	11,047	40,527	4,586,969	
	A.L.P.(N_f)	1,162	3,020	12,869	40,666	-	
	A.F.	250	96	23	7	1	
	Accuracy	92%	96%	86%	99%	-	89%
ST(1.5) + DLT(1.5)	Fatigue test (N_f)	2,776	6,023	26,687	87,815	5,150,684	
	A.L.P.(N_f)	2,968	7,393	29,551	88,758	-	
	A.F.	250	96	23	7	1	
	Accuracy	94%	81%	90%	99%	-	86%

A.L.P. : Acceleration Lifetime Prediction
A.F. : Acceleration Factor

4. Reliability assessment of the predicted life

Figs. 9 and 10 present reliability assessment, and Tables 6 and 7 illustrate the percentiles at 20% tensile strength of the plug- and ring-type gas-welded joints, respectively.

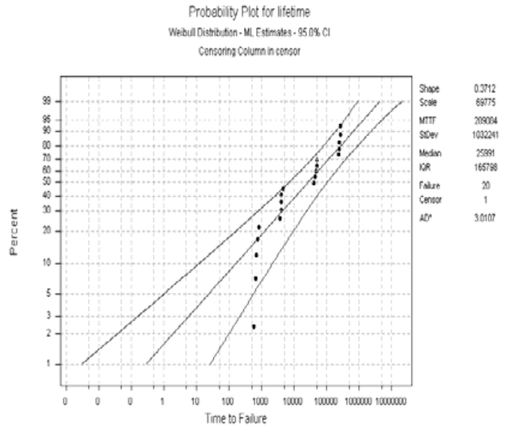


Fig. 9. Reliability estimation of the plug-type gas-welded joint (ST(1.5)+ST(1.5), for example).

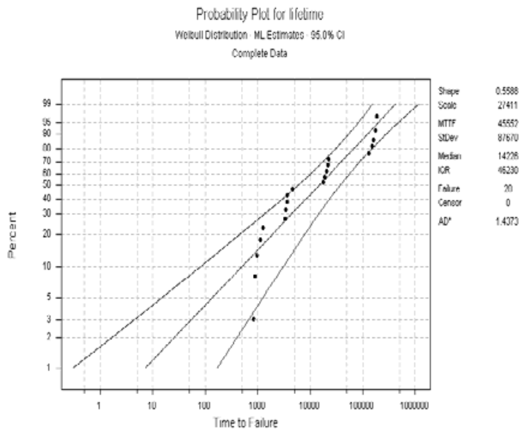


Fig. 10. Reliability estimation of the ring-type gas-welded joint (ST(1.5)+ST(1.5), for example).

4.1 Plug-type gas-welded joint

Under the assumption that the fatigue limit for the infinite life was 10^7 cycles, at 95% reliability level, probability that ST(1.5)+ ST(1.5), ST(1.5)+HT(1.5), and ST(1.5)+ DLT(1.5) joints were not failed was assessed in 90%, 92% and 89%, respectively. At 20% of the maximum tensile strength of the gas-welded joints, ST(1.5)+ST(1.5) joint was assed as the mean fatigue life = 230,358 cycles, and reliability range = (206,658~256,777)cycles at 95% reliability level and ± 15% standard deviation, ST(1.5)+HT(1.5) joint was assed as the mean fatigue life = 184,829 cycles, and reliability range = (147,545~231,533)cycles at 95% reliability level and ± 10% standard deviation, and ST(1.5)+DLT(1.5) joint was assed as the mean fatigue life = 113,002cycles, and reliability range = (98,938~129,067)cycles at 95% reliability level and ± 15% standard deviation, respectively.

4.2 Ring-type gas-welded joint

When the fatigue limit of plug-type gas-welded joint assumes as 10^7 cycles, at 95% reliability level, probability that ST(1.5)+ST(1.5), ST(1.5)+HT(1.5), and ST(1.5)+DLT(1.5) joints were not failed was assessed in 89%, 86% and 91%, respectively. At 20% of the maximum tensile strength of the gas-welded joints, ST(1.5)+ST(1.5) joint was assed as the mean fatigue life = 135,909 cycles, and reliability range = (111,958~164,983)cycles at 95% reliability level and ± 10% standard deviation, ST(1.5)+HT(1.5) joint was assed as the mean fatigue life = 32,827 cycles, and reliability range = (25,725~41,889)cycles at 95% reliability level and ± 10% standard deviation, and ST(1.5)+DLT(1.5) joint was assed as the mean fatigue life = 59,440cycles, and reliability range = (38,208~92,473)cycles at 95% reliability level and ± 15%

Table 6. Percentile of the plug-type gas-welded joint (for example, ST(1.5)+ST(1.5), 20% of tensile strength).

Table of Percentiles

Percent	Percentile	Standard Error	95.0% Normal CI Lower	95.0% Normal CI Upper
1	203862.7	19836.02	168467.1	246695.0
2	211400.5	17885.53	179097.8	249529.5
3	215962.5	16674.01	185634.6	251245.2
4	219276.2	15782.19	190426.4	252496.9
5	221895.4	15071.82	194237.1	253492.2
6	224070.3	14479.23	197415.1	254324.5
7	225935.8	13969.64	200149.8	255043.9
8	227573.2	13521.88	202555.8	255680.5
9	229035.5	13122.06	204708.1	256253.8
10	230358.8	12760.57	206658.4	256777.3
20	239525.9	10297.67	220169.8	260583.7
30	245439.5	8808.786	228767.9	263326.2
40	250067.2	7765.393	235301.2	265759.8
50	254067.8	7008.574	240696.0	268182.5
60	257782.0	6484.266	245381.3	270809.4
70	261468.3	6190.938	249611.6	273888.3
80	265444.8	6178.929	253606.4	277835.8
90	270434.8	6629.026	257749.3	283744.6
91	271064.7	6720.070	258208.5	284561.1
92	271738.7	6825.209	258685.5	285450.6
93	272467.7	6947.578	259185.4	286430.7
94	273267.3	7091.691	259715.4	287526.3
95	274161.0	7264.411	260286.4	288775.2
96	275187.2	7476.977	260915.9	290239.0
97	276414.9	7749.890	261635.2	292029.5
98	277992.2	8127.610	262510.2	294387.3
99	280360.3	8745.085	263733.7	298035.2

Table 7. Percentile of the ring-type gas-welded joint (for example, ST(1.5)+ST(1.5), 20% of tensile strength).

Table of Percentiles

Percent	Percentile	Standard Error	95.0% Normal CI Lower	95.0% Normal CI Upper
1	109199.4	18992.04	77656.69	153554.3
2	116535.2	17619.17	86648.77	156729.9
3	121076.9	16702.57	92392.76	158666.3
4	124423.9	15998.59	96706.42	160085.7
5	127097.9	15420.82	100198.6	161218.5
6	129337.2	14927.68	103152.7	162168.5
7	131271.8	14495.71	105725.0	162991.7
8	132980.4	14110.25	108011.1	163721.8
9	134514.3	13761.48	110074.4	164380.7
10	135909.3	13442.51	111958.9	164983.2
20	145746.4	11182.06	125398.2	169396.4
30	152252.8	9748.981	134295.5	172611.2
40	157431.6	8722.125	141232.0	175489.3
50	161970.3	7974.198	147071.5	178378.3
60	166234.9	7468.547	152222.8	181536.8
70	170515.8	7220.246	156935.7	185271.1
80	175187.5	7305.018	161439.4	190106.4
90	181128.7	7968.224	166165.6	197439.2
91	181884.9	8093.995	166693.1	198461.2
92	182695.6	8238.246	167241.8	199577.2
93	183574.1	8405.186	167817.8	200809.8
94	184539.9	8600.881	168429.5	202191.3
95	185622.1	8834.565	169089.8	203770.9
96	186868.1	9121.383	169819.1	205628.8
97	188363.6	9489.017	170654.2	207910.9
98	190292.7	9997.652	171672.8	210932.2
99	193205.4	10830.63	173102.3	215643.1

standard deviation, respectively.

5. Conclusions

In order to minimize variance in the process of fatigue-data production for determining the criterion of fatigue design, through the use of an accelerated life prediction technique, which is a statistical approach, the actual fatigue-test results, the $(\Delta\sigma_a)_R$-N_f relationship, and the accelerated $(\Delta\sigma_a)_R$-$(N_f)_{ALP}$ relationship were compared and analysed. The reliability of the various proposed fatigue-strength evaluation methods was verified statistically. The conclusions that can be drawn are as follows.

(1) The optimum statistical distribution for accelerated life prediction was analysed to be the lognormal distribution for the plug-type gas-welded joint of ST(1.5)+HT(1.5), and the Weibull distribution for the plug-type gas-welded joint and the ring-type gas-welded joints of both ST(1.5)+HT(1.5) and ST(1.5) +DLT(1.5).

(2) From the result of the accelerated life prediction through the actual fatigue-test data of the plug-type gas-welded joint; ST(1.5)+ ST(1.5), ST(1.5)+HT(1.5), and ST(1.5)+ DLT(1.5), the mean accuracy of the accelerated life prediction was assessed to be (81~86)% of the actual test life. In the case of the ring-type gas-welded joint, the mean accuracy of the predicted life was estimated to be (96~97)% of the actual test life.

(3) It is expected that the results from the analysis will prove to be a useful means of determining the criterion for fatigue design and of predicting a specific target life in the regime of short lives and high stresses.

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