FATIGUE DESIGN CURVES FOR 6061-T6 ALUMINUM*

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ABSTRACT

A request has been made to the ASME Boiler and Pressure Vessel Committee that 6061-T6 aluminum be approved for use in the construction of Class 1 welded nuclear vessels so it can be used for the pressure vessel of the Advanced Neutron Source research reactor. Fatigue design curves with and without mean stress effects have been proposed. A knock-down factor of two is applied to the design curve for evaluation of welds. The basis of the curves is explained. The fatigue design curves are compared to fatigue data from base metal and weldments.

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NOMENCLATURE

A = constant in Eq. 1

B = constant in Eq. 1

E = elastic modulus

N = fatigue life

R = ratio of minimum stress to maximum stress in a fatigue test

RA = percent reduction of area

S = strain amplitude times elastic modulus

S_a = allowable amplitude of alternating stress intensity

S_e = endurance limit

S_f = fatigue strength under fully reversed loading

S_f' = fatigue strength in presence of mean stress

S_m = mean stress

S_u = tensile strength

S_y = cyclic yield strength

1. INTRODUCTION

Oak Ridge National Laboratory (ORNL) has proposed a new facility for neutron research, centered around a new research reactor, called the Advanced Neutron Source (ANS) (West, 1988; Harrington, 1991). The reactor will require extensive use of 6061-T6 aluminum in the primary pressure boundary. The ANS is to be a user experimental facility for many scientific fields, including neutron scattering with cold, thermal, and hot neutrons (the most important scientific justification for the project); engineering materials irradiation; isotope production (including transuranium isotopes); materials analysis; and nuclear science. It is anticipated that the ANS will lead to important technological developments that will enhance our global competitiveness.

The user requirements, particularly the need for a large, accessible volume of a very high thermal neutron flux, determine the main features {high power [~300 MW(t)] and small size} of the reactor core design. The basic concept is conventional: a heavy-water-cooled and reflected reactor. The coolant inlet temperature is expected to be 45°C (113°F) and the bulk coolant outlet temperature is expected to be 85°C (185°F). The inlet pressure will be 3.5 MPa (508 psi). The primary pressure boundary is a long 0.5 m (20 in.) diameter 6061-T6 aluminum vessel with flanges on both ends so that it can be periodically replaced as required due to embrittlement caused by neutron irradiation. Outside the primary pressure boundary vessel, there will also be a 3.5 m (11.5 ft) diameter 6061-T6 aluminum reflector tank with numerous penetrations and attachments that will contain heavy water at a pressure of about 0.5 MPa (75 psig). The heavy water in the reflector tank will be at a temperature below 46°C (115°F).

Aluminum has been employed as a structural material in most research reactors. The aluminum alloy 6061-T6 has been successfully used in structural applications in several research reactors including the High Flux Isotope Reactor (HFIR) at Oak Ridge and the High Flux Beam Reactor (HFBR) at Brookhaven National Laboratory. The HFBR reactor vessel is 6061-T6 aluminum. It was designed in accordance with the ASME Boiler and Pressure Vessel Code for Unfired Pressure Vessels, Section VIII (1959), including all revisions, addenda, and applicable code case rulings in effect at the date of award of the construction contract. In addition, critical areas of the vessel where discontinuity stresses could be appreciable were examined and analyzed in accordance with the document "Tentative Structural Design Basis for Reactor Pressure Vessels and Directly Associated Components" (1958) along with formulae from reports, documents and publications by Bijlaard, Horvay, Galletly, et al.

Previous Department of Energy (DOE) research reactors have not been required to be built according to the ASME Nuclear Code. However, DOE Order 5480.4 *Environmental Protection, Safety, and Health Protection Standards* (1984) specifically requires all DOE and DOE contractor operations to apply the *ASME Boiler and Pressure Vessel Code* to DOE-owned reactors. Therefore, it will be necessary that the materials of construction for the ANS, including 6061-T6 aluminum, be acceptable Code materials.

A proposed Section III Code Case has been prepared for the ASME Boiler and Pressure Vessel Committee's consideration. The basis for the design fatigue curves included in the proposed Code Case is provided in this paper.

2. BASIC FATIGUE CURVE

Fatigue data on 6061-T6 aluminum were collected from the literature (*Structural Alloys Handbook*, 1989; *Alcoa Structural Handbook*, 1960; MIL-HDBK-5D, 1984; AFML-TDR-64-280, 1970; Brodrick and Spiering, 1972) to construct a design fatigue curve. The data are plotted in Fig. 1. Data for test temperatures from room temperature up to 149°C (300°F) are included. The data are for fully reversed loading. The low cycle data ($<10^3$ cycles) are all from axial strain controlled tests. Note that the data from the strain controlled tests fall right in with the rest of the data at greater than 10^3 cycles. Some of the high cycle data are from rotating beam tests. A fit to the 6061-T6 fatigue data was developed using the equation given in the Code Section III criteria document (1969).

$$S = \frac{E}{4\sqrt{N}}\ln\left(\frac{100}{100-A}\right)+B \ , \tag{1}$$

where E = elastic modulus

N = number of cycles to failure

S = strain amplitude times elastic modulus

and A and B are constants that are selected to make the equation fit the data. Note that S is treated like a stress based on the assumption of elastic behavior. However, it does not represent a real stress when the elastic range is exceeded. As a first approximation, the fatigue properties can be estimated by taking A as the percentage reduction of area in a tensile test, RA, and B as the endurance limit S_e. It should be noted that aluminum does not exhibit an endurance limit. The fit to the data is

$$S = \frac{14,479}{\sqrt{N}} + 96.5 \text{ MPa}$$

$$\text{or } S = \frac{2,100,000}{\sqrt{N}} + 14,000 \text{ psi.}$$

The curve is shown with the available data from tests without any mean stress in Fig. 1. It was used to construct the design curve by reducing the stress by a factor of two or the number of cycles to failure by twenty as shown in Fig. 2. The design curve is truncated at twice the yield strength to prevent significant strain accumulation.

3. MEAN STRESS EFFECTS

Data from fatigue tests (*Structural Alloys Handbook*, 1989; MIL-HDBK-5D, 1984) with an applied mean stress fall below the fit to the fully reversed fatigue data as shown in Fig. 3. The mean stress data include test series with constant R ratios as high as +0.5 and test series with applied mean stress of up to 207 MPa (30 ksi). Mean stress effects are generally accounted for by use of the modified Goodman diagram (ASME Criteria Document, 1969) when the fatigue curves in the ASME Boiler and Pressure Vessel Code are developed. Experimental studies of aluminum (Fuchs and Stephens, 1980; Woodward, et al., 1956) show that the mean stress effect is better described by the Gerber equation

$$S_f' = S_f [1 - (\frac{S_m}{S_u})^2] , \qquad (2)$$

than by the linear Goodman equation

$$S_f' = S_f (1 - \frac{S_m}{S_u}) , \qquad (3)$$

where S_f' = fatigue strength in presence of mean stress

S_f = fatigue strength under fully reversed cycling

S_m = mean stress

S_u = tensile strength.

The modified Goodman diagram is generally used because it is simpler to apply than the Gerber equation and is more conservative. However, for materials that have a high yield

strength to tensile strength ratio, such as 6061-T6 aluminum or high strength steel bolts, the modified Goodman approach tends to become overly conservative. The mean stress effect in high strength bolts was accounted for using the Peterson cubic equation when the Code fatigue curves were developed (Snow and Langer, 1967).

The Gerber equation and the linear Goodman equation are represented in Fig. 4. The alternating stress is represented on the ordinate and the mean stress is represented on the abscissa. The straight solid line drawn from the fatigue strength for fully reversed loading for 200,000 cycles [129 MPa (18.7 ksi)] to the tensile strength [290 MPa (42 ksi)] is a graphical representation of the Goodman prediction of the effect of mean stress. The Gerber prediction is the curved line. The dashed line drawn between the cyclic yield stress [262 MPa (38 ksi)] on both axes represents the boundary of sustained cyclic conditions; yielding will occur if the combination of alternating stress and mean stress is above the dashed line. Therefore, the intersection of the dashed line with the Goodman or Gerber line gives the maximum effect of mean stress because yielding would reduce any higher mean stress. For the case of 200,000 cycles shown in Fig. 4, the Goodman approach would predict a maximum reduction in fatigue strength to [22 MPa (3.2 ksi)]. Using the Gerber approach, the maximum reduction is to [75 MPa (10.94 ksi)]. For this case, the allowable alternating stress is increased by three times because the Gerber approach was used instead of the Goodman approach.

The difference between the maximum mean stress effect predicted by the Gerber and Goodman approaches becomes much more significant when the yield strength approaches the tensile strength, especially for low fatigue strengths.

Studies by Brodrick and Stephens (1972); and Chung and Abel, (1988) have shown that 6061-T6 cyclically hardens a small amount at room temperature [typically 241 MPa (35 ksi) to 262 MPa (38 ksi)]. At 149°C (300°F) it cyclically softens at total strain ranges below about two percent and cyclically hardens at higher total strain ranges.

Because 6061-T6 aluminum cyclically hardens, a value of 262 MPa (38 ksi) was used for the yield strength when determining the maximum effect of mean stress. This does result in lower values of allowable alternating stress than would have been obtained if the monotomic yield strength of 241 MPa (35 ksi) had been used. [For example, the maximum mean stress reduction in the 200,000 cycle fatigue strength would have been to 93 MPa (13.5 ksi) instead of to 75 MPa (10.94 ksi).]

Yield and ultimate strengths of 262 MPa (38 ksi) and 290 MPa (42 ksi), respectively, were used in making the mean stress corrections to the best fit to the fatigue data. The resulting curve shown in Fig. 5 was then reduced by a factor of two on stress or twenty on number of cycles to failure to arrive at a design curve that considers the effects of the maximum amount of mean stress that could be sustained.

The design curves with zero mean stress and with maximum mean stress are shown in Fig. 6. The design curves are both truncated at twice the minimum yield strength to help guard against excessive strain. Tabular values of allowable alternating stress are given in Table 1.

4. FATIGUE OF WELDED 6061-T6 ALUMINUM

The fatigue behavior of aluminum alloy weldments has been surveyed by Sanders (1971), Sanders and Lawrence (1978), and Sanders and Day (1983). Weldment fatigue data for 6061-T6 aluminum from Sanders and Day (1983) are compared with the design fatigue curves with no mean stress effect and with maximum mean stress effect in Fig. 7. This comparison seems to indicate that the design curve with maximum mean stress effect would be adequate for weldments.

Considerable testing on transverse butt joints in 9.5 mm (3/8 in.) thick 6061-T6 aluminum plate welded by the inert-gas tungsten-arc process using 4043 electrodes was reported by Hartmann, et al. (1954). The gage section was 139.7 mm (5.0 in.) wide and 393.7 mm (15.5 in.) long. The tests were conducted in Alcoa's Aluminum Research Laboratories' Structural Fatigue Testing Machines which loaded the specimens axially with a tensile stress range from zero to a maximum stress (R=0). In general, the fatigue specimens with the weld bead left in the as-welded condition failed at the edge of the bead; however, a few specimens with very smooth weld bead failed in the heat-affected zone. The majority of the fatigue failures in specimens in which the weld bead was removed occurred in the heat-affected zone with about 20 percent of the failures occurring through the weld. Nordmark and Clark (1964) extended those tests to include a number of different stress ratios. Comparison of data from Nordmark and Clark (1964) with the design curves in Fig. 8 shows that the design curve with maximum mean stress effects is not adequate for weldments subjected to cycles with high mean stress.

It should be noted that fatigue allowables for welded 6061-T6 aluminum are included in specifications suggested by the American Society of Civil Engineers (ASCE) Task Committee on Lightweight Alloys (1962). The fatigue allowables in the ASCE specification were based on the data from Nordmark and Clark (1964). The ASCE design curves are compared with the proposed design fatigue curves in Fig. 9. Note that the ASCE fatigue design curve for welded joints with an R-ratio of 0.5 is in good agreement with the design curve with maximum mean stress effects and a weld reduction factor of two. Therefore, a weld reduction factor of two must be applied to the fatigue design curves when they are applied to welds.

The fatigue design curve reduced by a factor of two on stress is compared with the data from Sanders and Day (1983) and Nordmark and Clark (1964) for weldments in Fig. 10. The open point symbols are from tests with no mean stress. The plus and x symbols are from tests with applied mean stress. As can be seen in Fig. 10, a weld reduction factor of two, i.e. dividing the allowable stress values by two, results in design curves that are adequately conservative.

5. SUMMARY

Fatigue design curves have been developed for 6061-T6 aluminum and are given in Fig. 6 and Table 1. Mean stress effects were accounted for using the Gerber equation. A weld reduction factor of two is required when the fatigue design curves are applied to welds.

6. ACKNOWLEDGMENTS

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Table 1. Tabulated values of Sa from Fig. 6.

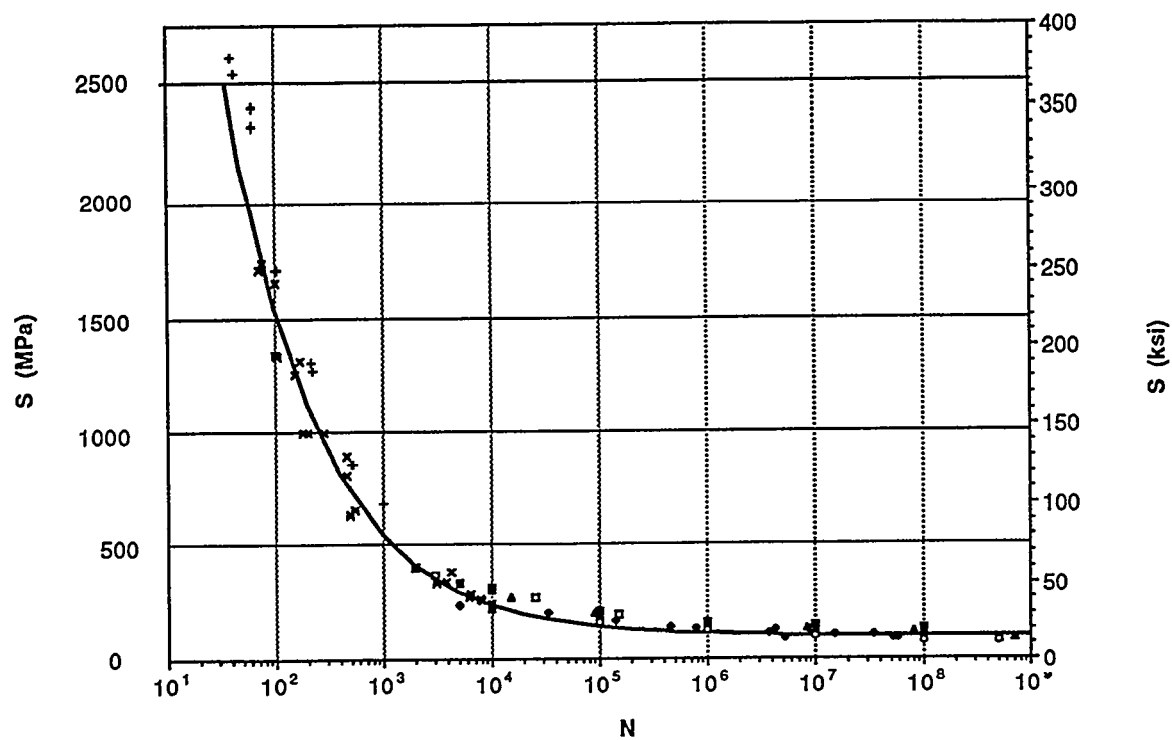| Number of Cycles	Sa			
	Zero mean stress		Maximum mean stress	
	(MPa)	(ksi)	(MPa)	(ksi)
1.0E+01	482.63	70.00	482.63	70.00
2.0E+01	482.63	70.00	482.63	70.00
5.0E+01	482.63	70.00	482.63	70.00
7.0E+01	482.63	70.00	482.63	70.00
1.0E+02	420.28	60.96	420.28	60.96
2.0E+02	325.43	47.20	325.43	47.20
5.0E+02	241.32	35.00	239.94	34.80
1.0E+03	198.91	28.85	184.71	26.79
2.0E+03	168.92	24.50	137.89	20.00
5.0E+03	142.31	20.64	95.01	13.78
7.0E+03	135.83	19.70	75.36	10.93
1.0E+04	120.66	17.50	63.02	9.14
2.0E+04	99.46	14.43	53.37	7.74
5.0E+04	80.64	11.70	49.50	7.18
1.0E+05	71.15	10.32	47.50	6.89
2.0E+05	64.45	9.35	37.68	5.47
5.0E+05	58.50	8.49	30.06	4.36
1.0E+06	55.50	8.05	26.68	3.87
2.0E+06	53.38	7.74	24.48	3.55
5.0E+06	51.50	7.47	22.68	3.29
1.0E+07	50.55	7.33	21.79	3.16
2.0E+07	49.88	7.24	21.18	3.07
5.0E+07	49.28	7.15	20.66	3.00
1.0E+08	48.99	7.11	20.39	2.96
2.0E+08	48.77	7.07	20.21	2.93
5.0E+08	48.59	7.05	20.06	2.91
1.0E+09	48.49	7.03	19.97	2.90

Fig. 1 Fit to fully reversed 6061-T6 fatigue data.
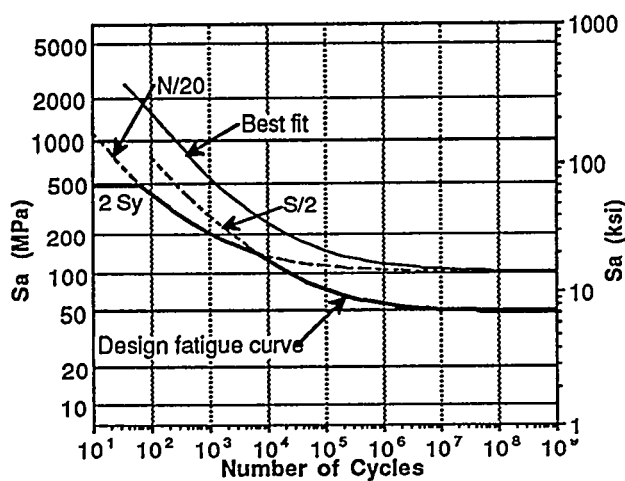

Fig. 2. Design fatigue curve is constructed by reducing fit to data by factor of 20 on life and 2 on stress.
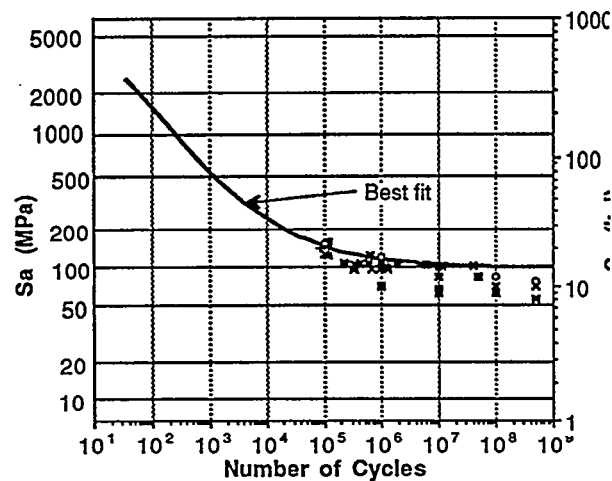

Fig. 3. Fatigue test data from tests with applied mean stress fall below fit to fully reversed fatigue data.
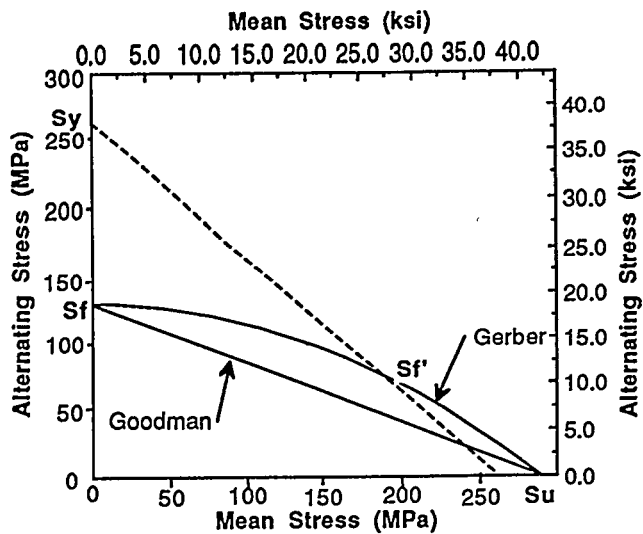
Fig. 4. Comparison of Gerber and Goodman mean stress corrections at 200,000 cycles.
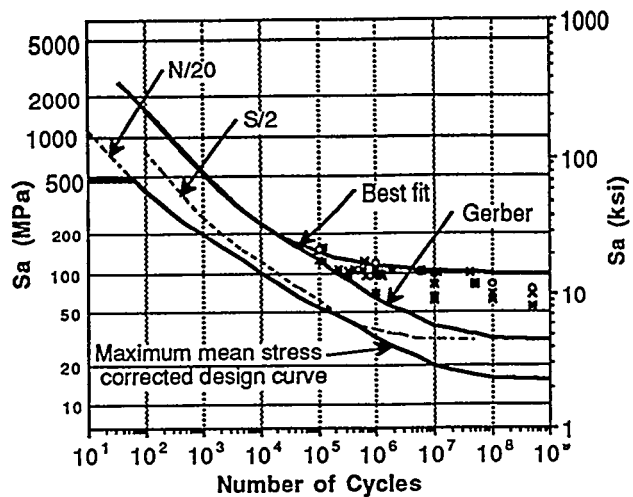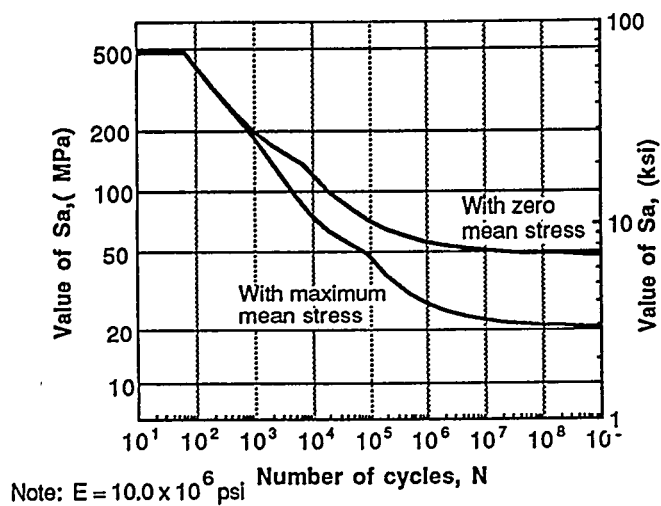

Fig. 5 Gerber mean stress correction provides lower bound to data from tests with mean stress.

Note: $E = 10.0 \times 10^6$ psi

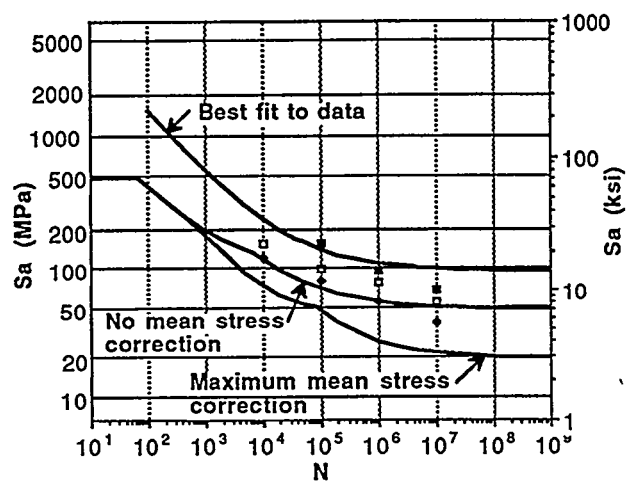Fig. 6. Fatigue design curves for 6061-T6 aluminum.

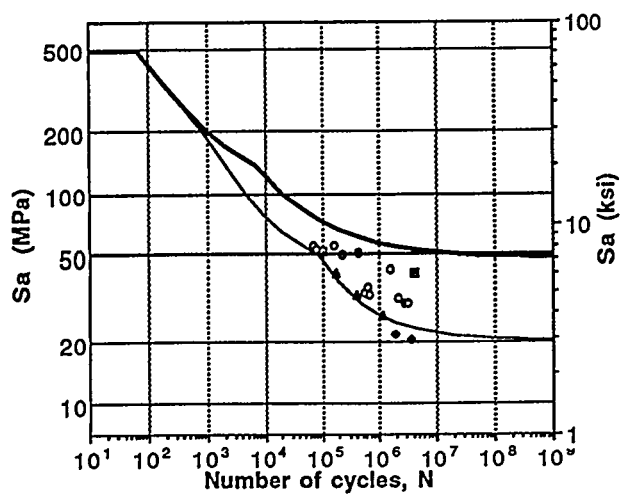Fig. 7. Weldment fatigue data for 6061-T6 aluminum.

Fig. 8. Data from fatigue tests on weldments with applied mean stress compared with design fatigue curves
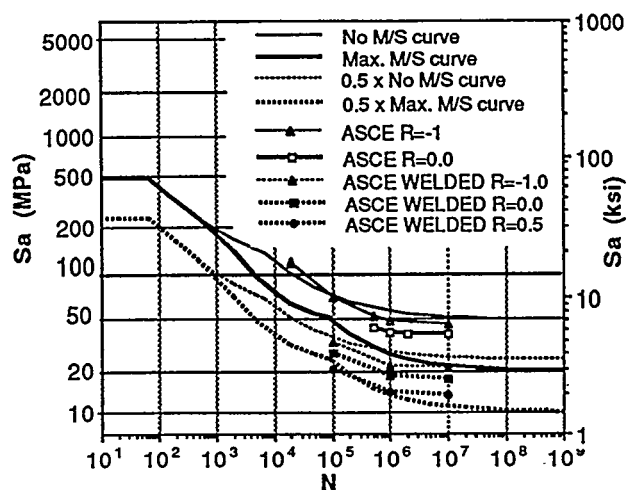

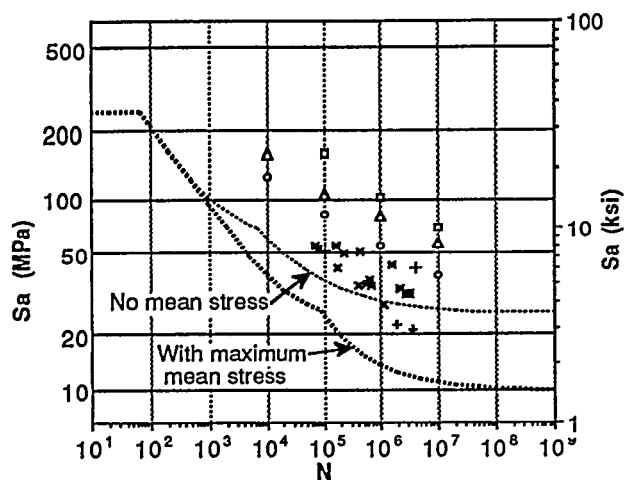Fig. 9. Proposed fatigue curves compared with ASCE fatigue allowables.

Fig. 10. Proposed fatigue design curves fall well below data when weld reduction factor of two is applied.