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PREVENTION OF NON-DUCTILE FRACTURE IN 6061-T6 ALUMINUM NUCLEAR PRESSURE VESSELS*

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ABSTRACT

The American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Committee has approved rules for the use of 6061-T6 and 6061-T651 aluminum for the construction of Class 1 welded nuclear pressure vessels for temperatures not exceeding 149°C (300°F). Nuclear Code Case N-519 will allow the use of this aluminum in the construction of low temperature research reactors such as the Advanced Neutron Source. The rules for protection against non-ductile fracture are discussed. The basis for a value of 25.3 MPa$\sqrt{m}$ (23 ksi $\sqrt{in.}$) for the critical or reference stress intensity factor for use in the fracture analysis is presented. Requirements for consideration of the effects of neutron irradiation on the fracture toughness are discussed.

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 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 around the reactor core is a long 0.5 m (20 in.) diameter 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 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).

The high nuclear-induced internal heat generation rate near the reactor core in the primary pressure boundary vessel, and the desire to preserve the maximum number of neutrons, led to the choice of aluminum as the primary pressure boundary material. 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.

Code Case N-519 — "Use of 6061-T6 and 6061-T651 Aluminum for Class 1 Nuclear Components" (1994) was approved by the ASME Board on Nuclear Codes and Standards on April 7, 1994. Nuclear Code Case N-519 will allow the use of welded 6061-T6 aluminum in the construction of low temperature research reactors such as the ANS. The principal developments required for Code Case N-519 were fatigue curves and procedures for protection against non-ductile fracture. The fatigue curves were discussed in a previous paper (Yahr, 1993). The rules for protection against non-ductile fracture are discussed here. The basis for the selected value of critical or

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reference stress intensity factor for use in the fracture analysis is presented. Requirements for consideration of the effects of neutron irradiation on the fracture toughness are discussed. Data from tests in the HFIR that show the effects of irradiation on 6061-T651 aluminum are discussed.

ASME CODE APPROACH TO PREVENTION OF NON-DUCTILE FAILURE

The ASME Boiler and Pressure Vessel Code, Section III, (1992), emphasizes the use of ductile materials for construction of Class 1 nuclear components. Article NB-2300 requires impact testing to assure that the materials used have adequate fracture toughness. Austenitic stainless steels and nonferrous material are exempt from impact test requirements.

Paragraph NB-321(d) further requires an evaluation of service and test conditions by methods similar to those contained in Appendix 6 except for piping, pump, and valve material. Appendix 6 is based on the fracture mechanics approach recommended by the Pressure Vessel Research Committee's Ad Hoc Task Group on Toughness Requirements (1972). Appendix G includes a curve in Fig. G-2210-1 that gives a lower bound value of the critical, or reference, stress intensity factor K_{IR} as a function of a temperature which is related to the reference nil ductility temperature determined by impact testing. The curve is applicable to ferritic steels with a specified minimum strength of 34 MPa (50.0 ksi) or less at room temperature, and may be used for materials which have specified minimum yield strengths at room temperature up to 621 MPa (90.0) ksi provided data are included in the Design Specification that demonstrate that the toughness of the material lies above the curve in Fig. G-2210-1 even after radiation. Appendix G requires that one postulate a sharp surface defect normal to the direction of normal stress that has a depth of one-fourth of the section thickness and a length of 1.5 times the section thickness. For sections less than 102-mm (4-in.) thick, the 25.4-mm (1-in.) deep defect is conservatively postulated. Smaller defect sizes may be used on an individual case basis if a smaller size of maximum postulated defect can be ensured. In order to assure that brittle fracture will not occur for service level A and B loadings, the sum of twice the calculated stress intensity factor produced by primary stresses plus the stress intensity factor due to a thermal gradient through the thickness must not exceed the critical, or reference, stress intensity factor K_{IR}.

UNIRRADIATED FRACTURE BEHAVIOR OF 6061-T6 ALUMINUM

Aluminum alloys, including 6061-T6, have a face-centered-cubic crystal structure. Under normal circumstances face-centered-cubic crystal structures do not exhibit cleavage fractures even at very low temperatures (Broek, 1986) (Barsom and Rolfe, 1987). The fracture mode is the same no matter what the temperature. Thus, the transition temperature phenomenon that is common to pressure vessel steels does not exist in aluminum alloys (Zinkham and Dedrick, 1969). Unlike steels, aluminum alloys exhibit toughness values at cryogenic temperatures that are about the same as at room-temperature.

Another characteristic of aluminum alloys is that they are rate insensitive (Broek, 1986) (Barsom and Rolfe, 1987). Thus, unlike pressure vessel steels, there is little difference in the value of K_{Ic} determined from tests at slow loading rates and the value of K_{Id} determined from tests at impact or dynamic loading rates.

The fracture toughness data in Table 1 from over 185 tests were collected from sixteen sources (Chu and Wacker, 1972) (Albertin and DeMastry, 1972) (Nelson and Kaufman, 1973) (Nelson and Brownhill, 1977) (Barker, 1979) (Alexander, 1993) (Structural Alloys Handbook, 1989)(MIL-HDBK-SD, 1984) (MCIC-HB-04, 1977) (Schwarmann, 1988) (Aerospace Structural Metals Handbook, 1973) (ALFRAC, 1993) (McConnell et al., 1986) (Kapp, 1985) (Succop and Brown, 1977) (Shannon et al., 1977). The product forms included plates from 12.7-mm to 127-mm thick, 63.5 mm diameter bar and various sizes of forgings. Weldments using either 4043 or 5356 weld rods were tested in both the as-welded condition and after post weld heat-treatment. Test temperatures ranged from -196°C to 150°C, but most tests were conducted at room temperature.

A large number of tests did not meet the validity requirements given in the appropriate ASTM standard. Data from almost 100 tests were reported in the literature as K_{Ic} values. The minimum value reported for K_{Ic} was 23.1 MPa$\sqrt{m}$ (21 ksi$\sqrt{in.}$) for specimens tested at room temperature with the crack oriented in the S-L direction. The key to the crack orientation is given in Figs. 1–3 (ASTM Spec. E399, 1990) (Chu and Wacker, 1972). As can be seen in Fig. 1, crack propagation in the S-L orientation is not likely to occur in a pressure vessel. The lowest value reported for K_{Ic} for any orientation that could potentially occur in a pressure vessel was 25.3 MPa$\sqrt{m}$ (23 ksi$\sqrt{in.}$). This value was measured at room temperature on a 4043 weld in 76.2 mm (3 in.) thick plate without any post-weld heat-treatment. The average room temperature K_{Ic} value was 32.0 MPa$\sqrt{m}$ (29.1 ksi$\sqrt{in.}$) with a range from 25.3 MPa$\sqrt{m}$ (23 ksi $\sqrt{in.}$) to 36.3 MPa$\sqrt{m}$ (33.0 ksi$\sqrt{in.}$) if the data from specimens with the crack in the S-L orientation are excluded.

Data from tests that did not meet the ASTM requirements for a valid K_{Ic} value were generally reported as K_q. The average K_q value at room temperature was 32.3 MPa$\sqrt{m}$ (39.4 ksi$\sqrt{in.}$) with a range from 26.9 MPa$\sqrt{m}$ (24.5 ksi$\sqrt{in.}$) to 44.4 MPa$\sqrt{m}$ (40.4 ksi$\sqrt{in.}$). This agrees well with the K_{Ic} data. Alexander reported his data as K_j which averaged 33.1 MPa$\sqrt{m}$ (30.2 ksi$\sqrt{in.}$).

The fracture toughness is slightly lower at temperatures above room temperature and higher at temperatures below room temperature. Alexander's data shows that K_j averaged 33.1 MPa$\sqrt{m}$ (30.1 ksi$\sqrt{in.}$), 30.3 MPa$\sqrt{m}$ (27.6 ksi$\sqrt{in.}$), and 32.1 MPa$\sqrt{m}$ (29.2 ksi$\sqrt{in.}$) at room temperature, 95°C, and 150°C respectively. Values of K_{Ic} at cryogenic temperatures of -196°C and -78°C averaged 39.1 MPa$\sqrt{m}$

(35.6 ksi $\sqrt{in.}$) and 34.8 MPa $\sqrt{m}$ (31.7 ksi $\sqrt{in.}$) compared to the room temperature average of 32.0 MPa $\sqrt{m}$ (29.1 ksi $\sqrt{in.}$).

A value of 25.3 MPa $\sqrt{m}$ (23.0 ksi $\sqrt{in.}$) is the critical, or reference, stress intensity value, K_{IR} that is specified in Code Case N-519. The only reported values that are lower were for the S-L orientation in plates. Because the stresses that would drive a crack in that orientation do not usually occur in pressure vessels, it is reasonable not to base the value of K_{IR} on those data.

IRRADIATED FRACTURE TOUGHNESS

The mechanism for irradiation damage in many materials, including pressure vessel steels, is displacement of atoms in the crystal lattice due to collisions with high energy neutrons. Thus, changes in toughness of steels are usually correlated with the fast fluence. Aluminum is transmuted to silicon by thermal neutrons. These silicon atoms are the principal hardening mechanism in aluminum alloys. The effect of irradiation on the tensile behavior of 6061-T6 aluminum is documented in the literature (Farrell and King, 1979)(Weeks et al., 1990). The yield and tensile strength are increased by irradiation and the tensile ductility is decreased. Charpy impact tests on highly irradiated 6061-T6 aluminum show a marked decrease in the impact strength (Weeks et al., 1993). Estimates from Weeks' Charpy data by Kassir (1989) indicated that the unirradiated value of K_{Ic} was 21.75 MPa $\sqrt{m}$ and that the value dropped to 8.7 MPa $\sqrt{m}$ after irradiation to a thermal neutron fluence of 4.2 x 10^{27} m^{-2}.

Albertin and DeMastry (1972) measured the effect of irradiation at cryogenic temperatures to a maximum fast fluence of 1.4 x 10^{22} m^{-2}. Those test results are given in Table 2. There is no appreciable effect of irradiation at this low fluence.

Alexander (1993) has conducted J-integral-resistance (JR) curve toughness tests on irradiated and unirradiated 0.45 T compact specimens (28.6 x 27.4 x 11.4-mm thick) of 6061-T651 aluminum plate. The specimens were irradiated to a maximum thermal neutron fluence of 1 x 10^{26} m^{-2}. The minimum thermal neutron fluence was forty percent of the peak fluence. The fast neutron fluence was half the thermal neutron fluence. The specimen temperature during the irradiation was in the range of 60°C to 114°C. Tests were conducted at room temperature, 95°C, and 150°C. The results are shown in Table 2. There is no degradation of the fracture toughness at 25°C or 95°C, and only a slight decrease at 150°C.

REQUIREMENTS FOR CONSIDERATION OF IRRADIATION EFFECTS

Code Case N-519 includes the following requirement to assure that components are removed from service before neutron irradiation reduces the fracture toughness enough to compromise their structural integrity.

> "This material is known to be susceptible to embrittlement as a result of neutron irradiation. When the component will be subjected to neutron irradiation during service, the Design Specification shall include requirements for consideration of the effects of neutron irradiation on the fracture toughness and requirements for replacement of components before they pose a hazard for brittle fracture. The designer shall establish the irradiated K_{IR} value. That value shall be used to determine when components must be replaced. An in-service surveillance program, similar to the one given in ASTM E 185-82 for light-water cooled nuclear power reactor vessels, shall be established to monitor the embrittlement of the reactor vessel material. If data from surveillance tests indicate that the established K_{IR} value is unconservative, the component replacement schedule must be modified appropriately. The designer shall ensure that loss of ductility in-service does not invalidate the 3 S_m limit on the range of primary plus secondary stress."

Alexander is extending his irradiation tests to thermal fluences of 8 x 10^{26} m^{-2} and to include weldments. These data will be used to establish an irradiated K_{IR} value for the ANS design and establish planned schedules for replacement of 6061-T651 components. Preliminary planning of a surveillance program for the ANS has been done by Heavilin (1995). A preliminary fracture analysis of the ANS core pressure boundary tube has been done by Schulz (1995).

SUMMARY

Code Case N-519 allows the use of 6061-T6 and 6061-T651 aluminum in the construction of Section III, Division 1, Class 1 welded pressure vessels at temperatures not exceeding 149°C (300°F). The two major developments necessary for this Code Case were fatigue curves and procedures for protection against non-ductile fracture. The basis for the fatigue curves was presented earlier (Yahr, 1993). The basis for the rules for protection against non-ductile rupture have been presented here. A single value of 25.3 MPa $\sqrt{m}$ (23.0 ksi $\sqrt{in.}$) for the critical, or reference, stress intensity factor K_{IR} is used in an Appendix G type analysis instead of the temperature-dependent values given in Fig. G-2210-1 of the Code for steels.

Because of a potential decrease in fracture toughness of 6061-T6 aluminum due to neutron irradiation, the designer must establish an irradiated K_{IR} value that will exceed the materials fracture toughness at the end of life and show that non-ductile fracture will not occur if the fracture toughness does not fall below that value of K_{IR}. An in-service surveillance program must be established to monitor the irradiation-induced embrittlement of the vessel material. If the measured fracture toughness of the surveillance tests indicates that the established K_{IR} value is not conservative, the component must be removed from service.

It should be noted that Code Case N-519 applies only to 6061-T6 aluminum. Limited data in the literature suggest that some other aluminum alloys, in particular 5000 series aluminum, retain much lower tensile ductility than 6061-T6 aluminum. The ductility of 6061-T6 aluminum was a major concern to several Code Committee members so materials with less ductility would deserve critical evaluation.

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TABLE 1. FRACTURE TOUGHNESS DATA FOR 6061-T6, 6061-T651, AND 6061-T652 ALUMINUM.

Material	Temp. (C)	Specimen Type	Specimen Size (mm)	Crack Orr.	No. of Spec.	Kq (MPa $\sqrt{m}$)	Kmax (MPa $\sqrt{m}$)	Kj (MPa $\sqrt{m}$)	Klc (MPa $\sqrt{m}$)	Notes	Reference
31.8-76.2 mm plate 6061-T651	24		12.7-31.8	SL	6				23.1	AVG	MIL-HDBK-5D
31.8-76.2 mm plate 6061-T651	24		12.7-31.8	SL	1				23.1	MIN	MIL-HDBK-5D
76.2 mm plate 6061-T651	22	Compact	63.5	SL	1	23.2	23.5		23.2		Nelson & Kaufman
6061-T651				SL					23.4		Schwarmann
76.2 mm plate 6061-T651	22	Compact	63.5	SL	1	23.4	23.8		23.4		Nelson & Kaufman
76.2 mm plate 6061-T651	22	Compact	32	SL			24.0		23.4		Nelson & Brownhill
76.2 mm plate 6061-T651	22	Compact	63.5	SL	1	23.7	24.0		23.7		Nelson & Kaufman
76.2 mm plate 6061-T651	22	UPE estimate		SL					24.2		Nelson & Brownhill
76.2 mm plate 6061-T651	-73	UPE estimate		SL					25.3		Nelson & Brownhill
4043 Weld-76.2 mm plate 6061-T651-no post weld ht	22	UPE estimate		TL					25.3		Nelson & Brownhill
229x610x610 mm forging 6061-T652	22	Notch-bend	25.4	TW	1		25.7		25.7		Chu & Wacker
76.2 mm plate 6061-T651	24	Compact	31.75	SL	1	26.3			26.3		ALFRAC
76.2 mm plate 6061-T651	22	Compact	76	TL			30.9		26.4		Nelson & Brownhill
76.2 mm plate 6061-T651	-196	Compact	32	SL			27.3		26.6		Nelson & Brownhill
76.2 mm plate 6061-T651	-73	UPE estimate		TL					27.5		Nelson & Brownhill
4043 Weld-76.2 mm plate 6061-T651-no post weld ht	-73	UPE estimate		TL					27.5		Nelson & Brownhill
25.4-50.8 mm plate 6061-T651	24	Notch-bend		TL	1				27.8	MIN	MCIC-HB-04
229x610x610 mm forging 6061-T652	22	Notch-bend	25.4	TW	1		27.9		27.9		Chu & Wacker
127 mm plate 6061-T651	24	Compact	50.80	SL	1	28.0			28.0		ALFRAC
31.8-76.2 mm plate 6061-T651	24		30.5-76.2	TL	1				28.6	MIN	MIL-HDBK-5D
76.2 mm plate 6061-T651	24	Compact	63.37	TL	1	28.7			28.7		ALFRAC
25.4-50.8 mm plate 6061-T651	24	Notch-bend		TL	2				29.0	AVG	MCIC-HB-04
38.1 mm plate 6061-T651		Notch-bend	38.1	WL					29.1		Structural Alloys Hbk.
152x305x610 mm forging 6061-T652	22	Notch-bend	17.8	TR	1		29.2		29.2		Chu & Wacker
38.1 mm plate 6061-T651		Notch-bend	25.4	WL					29.2		Structural Alloys Hbk.
6061-T651				TL					29.4		Schwarmann
76.2 mm plate 6061-T651	-196	UPE estimate		TL					29.7		Nelson & Brownhill
38.1 mm plate 6061-T651	24			WL					29.7		ASMH
229x610x610 mm forging 6061-T652	22	Notch-bend	25.4	TR	1		29.8		29.8		Chu & Wacker
152x305x610 mm forging 6061-T652	22	Notch-bend	17.8	TR	1		29.8		29.8		Chu & Wacker
76.2 mm plate 6061-T651	22	Compact	76	LT			39.6		30.4		Nelson & Brownhill
127 mm plate 6061-T651	24	Compact	63.55	TL	1	30.5			30.5		ALFRAC
229x610x610 mm forging 6061-T652	22	Notch-bend	25.4	TR	1		30.5		30.5		Chu & Wacker
76.2 mm plate 6061-T651	22	UPE estimate		TL					30.8		Nelson & Brownhill
50.8 mm plate 6061-T651	24	Notch-bend	25.4	TL	3				30.8	AVG	Shannon, et. al.
31.8-76.2 mm plate 6061-T651	24		30.5-76.2	TL	4				30.8	AVG	MIL-HDBK-5D
25.4-50.8 mm plate 6061-T651	-78	Notch-bend		TL	1				30.8	MIN	MCIC-HB-04
76.2 mm plate 6061-T651	24	Compact	31.75	SL	1	31.0			31.0		ALFRAC
152x305x610 mm forging 6061-T652	22	Notch-bend	17.8	TW	1		31.8		31.8		Chu & Wacker
63.5 mm diam. 6061-T651	22	Short rod	38.1	CL	7	31.0			32.5		Barker
76.2 mm plate 6061-T651	-196	Compact	76	TL			35.4		32.7		Nelson & Brownhill
6061-T651				LT					32.9		Schwarmann
25.4-50.8 mm plate 6061-T651	-78	Notch-bend		TL	3				32.9	AVG	MCIC-HB-04
76.2 mm plate 6061-T651	-196	UPE estimate		SL					33.0		Nelson & Brownhill
31.8-76.2 mm plate 6061-T651	24		25.4-76.2	LT	1				33.0	MIN	MIL-HDBK-5D
38.1 mm plate 6061-T651	-80			WL					33.0		ASMH
31.8-76.2 mm plate 6061-T651	24		25.4-76.2	LT	4				34.1	AVG	MIL-HDBK-5D
63.5 mm diam. 6061-T651	22	Short rod	22	CL	4	30.2			34.1		Barker
31.8 mm plate 6061-T651	24	Compact	30.94	TL	1	34.3			34.3		ALFRAC

TABLE 1. FRACTURE TOUGHNESS DATA FOR 6061-T6, 6061-T651, AND 6061-T652 ALUMINUM. (CONT.)

Material	Temp. (C)	Specimen Type	Specimen Size (mm)	Crack Orr.	No. of Spec.	Kq $(MPa\sqrt{m})$	Kmax $(MPa\sqrt{m})$	Kj $(MPa\sqrt{m})$	KIc $(MPa\sqrt{m})$	Notes	Reference
63.5 mm diam. 6061-T651	22	Short rod	12.7	CL	2	27.8			34.5		Barker
63.5 mm diam. 6061-T651	22	Short rod	63.5	CL	4	33.1			34.7		Barker
76.2 mm plate 6061-T651	22	UPE estimate		LT					35.2		Nelson & Brownhill
6061-T651	27	Compact	25.4						35.2		Albertin & DeMastry
152x305x610 mm forging 6061-T652	22	Notch-bend	17.8	TW	1		35.3		35.3		Chu & Wacker
76.2 mm plate 6061-T651	24	Compact	63.47	LT	1	36.3			36.3		ALFRAC
76.2 mm plate 6061-T651	-73	UPE estimate		LT					36.3		Nelson & Brownhill
76.2 mm plate 6061-T651	-196	Compact	76	LT			42.6		38.0		Nelson & Brownhill
76.2 mm plate 6061-T651	-196	UPE estimate		LT					38.5		Nelson & Brownhill
4043 Weld-76.2 mm plate 6061-T651-no post weld ht	-196	UPE estimate		TL					38.5		Nelson & Brownhill
25.4-50.8 mm plate 6061-T651	-196	Notch-bend		TL	1				40.7	MIN	MCIC-HB-04
25.4-50.8 mm plate 6061-T651	-196	Notch-bend		TL	3				41.4	AVG	MCIC-HB-04
6061-T651	-196	Compact	25.4						42.8		Albertin & DeMastry
5356 Weld-76.2 mm plate 6061-T651-no post weld ht	22	UPE estimate		TL					42.9		Nelson & Brownhill
5356 Weld-76.2 mm plate 6061-T651-no post weld ht	-73	UPE estimate		TL					44.0		Nelson & Brownhill
6061-T651	-84	Compact	25.4						46.0		Albertin & DeMastry
6061-T651	-196	Compact	25.4						46.2		Albertin & DeMastry
5356 Weld-76.2 mm plate 6061-T651-no post weld ht	-196	UPE estimate		TL					64.8		Nelson & Brownhill
6061-T651 plate	24	Precracked Charpy		LT				51.9		Min.	Kapp
4043 Weld-76 mm plate 6061-T651-no post weld ht	22	Notch-bend	73.1		1	19.8	32.6				Nelson & Kaufman
5356 Weld-76 mm plate 6061-T651-no post weld ht	22	Notch-bend	73.1		1	20.4	53.3				Nelson & Kaufman
4043 Weld-76 mm plate 6061-T651-no post weld ht	22	Notch-bend	73.1		1	21.5	35.6				Nelson & Kaufman
4043 Weld-76 mm plate 6061-T651-no post weld ht	22	Notch-bend	73.1		1	21.8	36.8				Nelson & Kaufman
4043 Weld-76 mm plate 6061-T651-no post weld ht	22	Notch-bend	73.1		1	21.9	34.9				Nelson & Kaufman
5356 Weld-76 mm plate 6061-T651-post weld ht	22	Notch-bend	73.8		1	23.1	32.9				Nelson & Kaufman
5356 Weld-76 mm plate 6061-T651-post weld ht	22	Notch-bend	73.8		1	23.2	33.3				Nelson & Kaufman
76.2 mm plate 6061-T651	22	Compact	63.5	SL	1	23.3	24.3				Nelson & Kaufman
4043 Weld-76 mm plate 6061-T651-post weld ht	22	Notch-bend	74.2		1	23.4	34.1				Nelson & Kaufman
5356 Weld-76 mm plate 6061-T651-post weld ht	22	Notch-bend	73.7		1	24.2	34.1				Nelson & Kaufman
4043 Weld-76 mm plate 6061-T651-post weld ht	22	Notch-bend	74.5		1	24.4	33.2				Nelson & Kaufman
4043 Weld-76 mm plate 6061-T651-post weld ht	22	Notch-bend	74.7		1	25.5	29.7				Nelson & Kaufman
5356 Weld-76 mm plate 6061-T651-post weld ht	22	Notch-bend	74.8		1	26.5	30.1				Nelson & Kaufman
76.2 mm plate 6061-T651	24	Compact	74.98	TL	1	26.9					ALFRAC
Die forging 6061-T6	24	Compact	12.67	LT	1	27.1					ALFRAC

TABLE 1. FRACTURE TOUGHNESS DATA FOR 6061-T6, 6061-T651, AND 6061-T652 ALUMINUM. (CONT.)

Material	Temp. (C)	Specimen Type	Specimen Size (mm)	Crack Orr.	No. of Spec.	Kq (MPa $\sqrt{m}$)	Kmax (MPa $\sqrt{m}$)	Kj (MPa $\sqrt{m}$)	Klc (MPa $\sqrt{m}$)	Notes	Reference
4043 Weld-76 mm plate 6061-T651-post weld ht	22	Notch-bend	74		1	27.6	37.3				Nelson & Kaufman
127 mm plate 6061-T651	24	Compact	50.83	SL	1	27.8					ALFRAC
Die forging 6061-T6	24	Compact	12.67	TL	1	28.0					ALFRAC
Die forging 6061-T6	24	Compact	12.70	LT	1	28.2					ALFRAC
76.2 mm plate 6061-T651	22	Notch-bend	57.1	TL	1	28.8	31.8				Nelson & Kaufman
5356 Weld-76 mm plate 6061-T651-no post weld ht	22	Notch-bend	73.2		1	28.9	46.0				Nelson & Kaufman
76.2 mm plate 6061-T651	22	Notch-bend	76.6	TL	1	29.0	33.8				Nelson & Kaufman
127 mm plate 6061-T651	24	Compact	63.50	TL	1	29.1					ALFRAC
76.2 mm plate 6061-T651	24	Compact	63.50	TL	1	29.2					ALFRAC
Die forging 6061-T6	24	Compact	12.70	TL	1	29.8					ALFRAC
76.2 mm plate 6061-T651	22	Notch-bend	76.6	TL	1	29.8	34.9				Nelson & Kaufman
44.5 mm die forging 6061-T6	24	Compact	31.72	TL	1	30.3					ALFRAC
44.5 mm die forging 6061-T6	24	Compact	31.72	TL	1	30.4					ALFRAC
76.2 mm plate 6061-T651	24	Compact	74.75	LT	1	30.5					ALFRAC
Die forging 6061-T6	24	Compact	12.60	LT	1	30.7					ALFRAC
76.2 mm plate 6061-T651	22	Notch-bend	76.6	TL	1	30.7	34.9				Nelson & Kaufman
Die forging 6061-T6	24	Compact	12.60	TL	1	30.8					ALFRAC
44.5 mm die forging 6061-T6	24	Compact	31.75	LT	1	31.3					ALFRAC
5356 Weld-76 mm plate 6061-T651-no post weld ht	22	Notch-bend	73.1		1	32.0	50.0				Nelson & Kaufman
Die forging 6061-T6	24	Compact	12.70	LT	1	32.4					ALFRAC
76.2 mm plate 6061-T651	22	Notch-bend	76.8	LT	1	32.5	41.4				Nelson & Kaufman
76.2 mm plate 6061-T651	22	Notch-bend	57.2	LT	1	32.7	37.9				Nelson & Kaufman
12.7 mm plate 6061-T651	24	Compact	11.81	TL	1	33.1					ALFRAC
44.5 mm die forging 6061-T6	24	Compact	31.75	L-T	1	33.1					ALFRAC
76.2 mm plate 6061-T651	22	Notch-bend	76.7	LT	1	33.3	41.0				Nelson & Kaufman
76.2 mm plate 6061-T651	22	Notch-bend	76.7	LT	1	33.6	42.1				Nelson & Kaufman
76.2 mm plate 6061-T651	24	Compact	63.50	LT	1	34.5					ALFRAC
5356 Weld-76 mm plate 6061-T651-no post weld ht	22	Notch-bend	72.9		1	35.1	55.6				Nelson & Kaufman
Forged shape 6061-T6	24	Compact	25.43	TR	1	35.1					ALFRAC
25.4 mm plate 6061-T651	24	Compact	24.4856	TL	1	35.2					ALFRAC
127 mm plate 6061-T651	24	Compact	63.50	LT	1	35.4					ALFRAC
25.4 mm plate 6061-T651	24	Compact	24.49	TL	1	35.5					ALFRAC
127 mm plate 6061-T651	24	Compact	63.50	LT	1	35.6					ALFRAC
Forged shape 6061-T6	24	Compact	25.37	RT	1	35.6					ALFRAC
Forged shape 6061-T6	24	Compact	25.37	RT	1	35.6					ALFRAC
31.8 mm plate 6061-T651	24	Compact	30.91	LT	1	37.1					ALFRAC
Forged shape 6061-T6	24	Compact	25.40	TR	1	37.4					ALFRAC
330 mm forging 6061-T6	24	Compact	50.80	LT	1	37.9					ALFRAC
12.7 mm plate 6061-T651	24	Compact	11.81	LT	1	38.8					ALFRAC
330 mm forging 6061-T6	24	Compact	50.83	LT	1	39.0					ALFRAC
330 mm forging 6061-T6	24	Compact	50.83	LT	1	39.2					ALFRAC
50.8 mm die forging 6061-T6	24	Compact	19.08	CL	1	39.4					ALFRAC
330 mm forging 6061-T6	24	Compact	50.77	LT	1	39.7					ALFRAC
25.4 mm plate 6061-T651	24	Compact	24.49	LT	1	40.7					ALFRAC
330 mm forging 6061-T6	24	Compact	50.80	LT	1	40.9					ALFRAC
12.7 mm plate 6061-T651	24	Compact	11.94	TL	1	41.4					ALFRAC
330 mm forging 6061-T6	24	Compact	31.83	LT	1	41.6					ALFRAC

TABLE 1. FRACTURE TOUGHNESS DATA FOR 6061-T6, 6061-T651, AND 6061-T652 ALUMINUM. (CONT.)

Material	Temp. (C)	Specimen Type	Specimen Size (mm)	Crack Orr.	No. of Spec.	Kq ($MPa\sqrt{m}$)	Kmax ($MPa\sqrt{m}$)	Kj ($MPa\sqrt{m}$)	KIc ($MPa\sqrt{m}$)	Notes	Reference
38.1 mm plate 6061-T651	-196			WL		41.8					ASMH
50.8 mm die forging 6061-T6	24	Compact	19.05	CL	1	42.2					ALFRAC
25.4 mm plate 6061-T651	24	Compact	24.49	LT	1	42.3					ALFRAC
330 mm forging 6061-T6	24	Compact	50.80	LT	1	43.0					ALFRAC
12.7 mm plate 6061-T651	24	Compact	11.94	LT	1	44.4					ALFRAC
38.1 mm die forging 6061-T6	24	Compact	19.08	LC	1	45.6					ALFRAC
38.1 mm die forging 6061-T6	24	Compact	19.05	LC	1	47.6					ALFRAC
229x610x610 mm forging 6061-T652	22	Notch-bend	76.2	RT	1		47.5				Chu & Wacker
229x610x610 mm forging 6061-T652	22	Notch-bend	76.2	RT	1		53.5				Chu & Wacker
229x610x610 mm forging 6061-T652	22	Notch-bend	76.2	RW	1		40.9				Chu & Wacker
229x610x610 mm forging 6061-T652	22	Notch-bend	50.8	WR	1		39.2				Chu & Wacker
229x610x610 mm forging 6061-T652	22	Notch-bend	50.8	WR	1		39.1				Chu & Wacker
229x610x610 mm forging 6061-T652	22	Notch-bend	50.8	WT	1		50.0				Chu & Wacker
152x305x610 mm forging 6061-T652	22	Notch-bend	76.2	RT	1		72.4				Chu & Wacker
19.0 mm plate 6061-T651	21	Compact	11.4	TL	1			33.0			Alexander
19.0 mm plate 6061-T651	21	Compact	11.4	TL	1			33.8			Alexander
19.0 mm plate 6061-T651	26	Compact	11.4	TL	1			33.6			Alexander
19.0 mm plate 6061-T651	26	Compact	11.4	TL	1			32.1			Alexander
19.0 mm plate 6061-T651	95	Compact	11.4	TL	1			29.9			Alexander
19.0 mm plate 6061-T651	95	Compact	11.4	TL	1			30.8			Alexander
19.0 mm plate 6061-T651	95	Compact	11.4	TL	1			30.2			Alexander
19.0 mm plate 6061-T651	150	Compact	11.4	TL	1			32.3			Alexander
19.0 mm plate 6061-T651	150	Compact	11.4	TL	1			31.3			Alexander
19.0 mm plate 6061-T651	150	Compact	11.4	TL	1			32.6			Alexander
6061-T651	24	Compact	10.7					27.2			McConnell et al
6061-T651 plate	24	Precracked Charpy		LT				53.8		Max.	Kapp
6061-T651 plate	24	Precracked Charpy						32.2		Min.	Succop & Brown
6061-T651 plate	24	Precracked Charpy						35.2		Max.	Succop & Brown

TABLE 2. IRRADIATION EFFECTS ON FRACTURE TOUGHNESS.

Specimen Type	Specimen Size (mm)	Irradiation Temp. (C)	Test Temp. (C)	Thermal Fluence (m^{-2})	Fast Fluence (m^{-2})	K_a ($MPa\sqrt{m}$)	K_J ($MPa\sqrt{m}$)	Reference
Compact	24.5		-196		0	46.2		Albertin & DeMastry
Compact	24.5		-196		0	42.8		Albertin & DeMastry
Compact	24.5	-196	-196		1.3E+18	52.5		Albertin & DeMastry
Compact	24.5	-196	-196		1.3E+18	52.6		Albertin & DeMastry
Compact	24.5	-196	-196		1.4E+19	41.4		Albertin & DeMastry
Compact	24.5	-196	-196		1.3E+19	46.5		Albertin & DeMastry
Compact	24.5		-84		0	46		Albertin & DeMastry
Compact	24.5	-196	-84		1.3E+18	44.7		Albertin & DeMastry
Compact	24.5	-196	-84		1.3E+19	44.3		Albertin & DeMastry
Compact	24.5		27		0	35.2		Albertin & DeMastry
Compact	24.5	-196	27		1.3E+18	42.5		Albertin & DeMastry
Compact	24.5	-196	27		1.4E+19	42.6		Albertin & DeMastry
Compact	11.4		21	0	0		33	Alexander
Compact	11.4		21	0	0		33.8	Alexander
Compact	11.4		26	0	0		33.6	Alexander
Compact	11.4		26	0	0		32.1	Alexander
Compact	11.4	95	26	1.0E+26	5.0E+25		33.9	Alexander
Compact	11.4	95	26	1.0E+26	5.0E+25		34.8	Alexander
Compact	11.4	95	26	1.0E+26	5.0E+25		35.6	Alexander
Compact	11.4		95	0	0		29.9	Alexander
Compact	11.4		95	0	0		30.8	Alexander
Compact	11.4		95	0	0		30.2	Alexander
Compact	11.4	95	95	1.0E+26	5.0E+25		31.7	Alexander
Compact	11.4	95	95	1.0E+26	5.0E+25		32.2	Alexander
Compact	11.4		150	0	0		32.3	Alexander
Compact	11.4		150	0	0		31.3	Alexander
Compact	11.4		150	0	0		32.6	Alexander
Compact	11.4	95	150	1.0E+26	5.0E+25		30.5	Alexander
Compact	11.4	95	150	1.0E+26	5.0E+25		27.3	Alexander

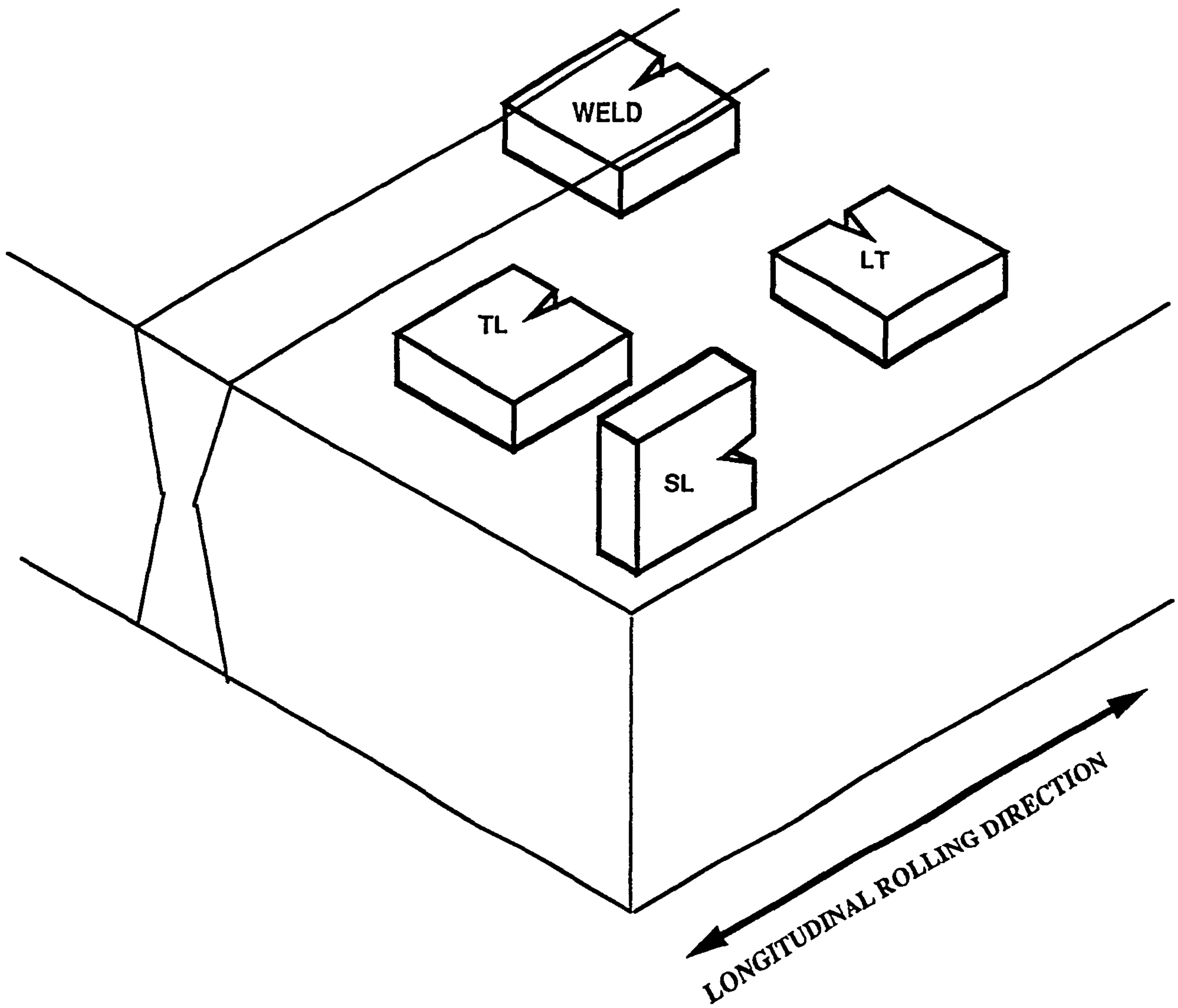

FIG. 1. CRACK ORIENTATIONS IN PLATES.

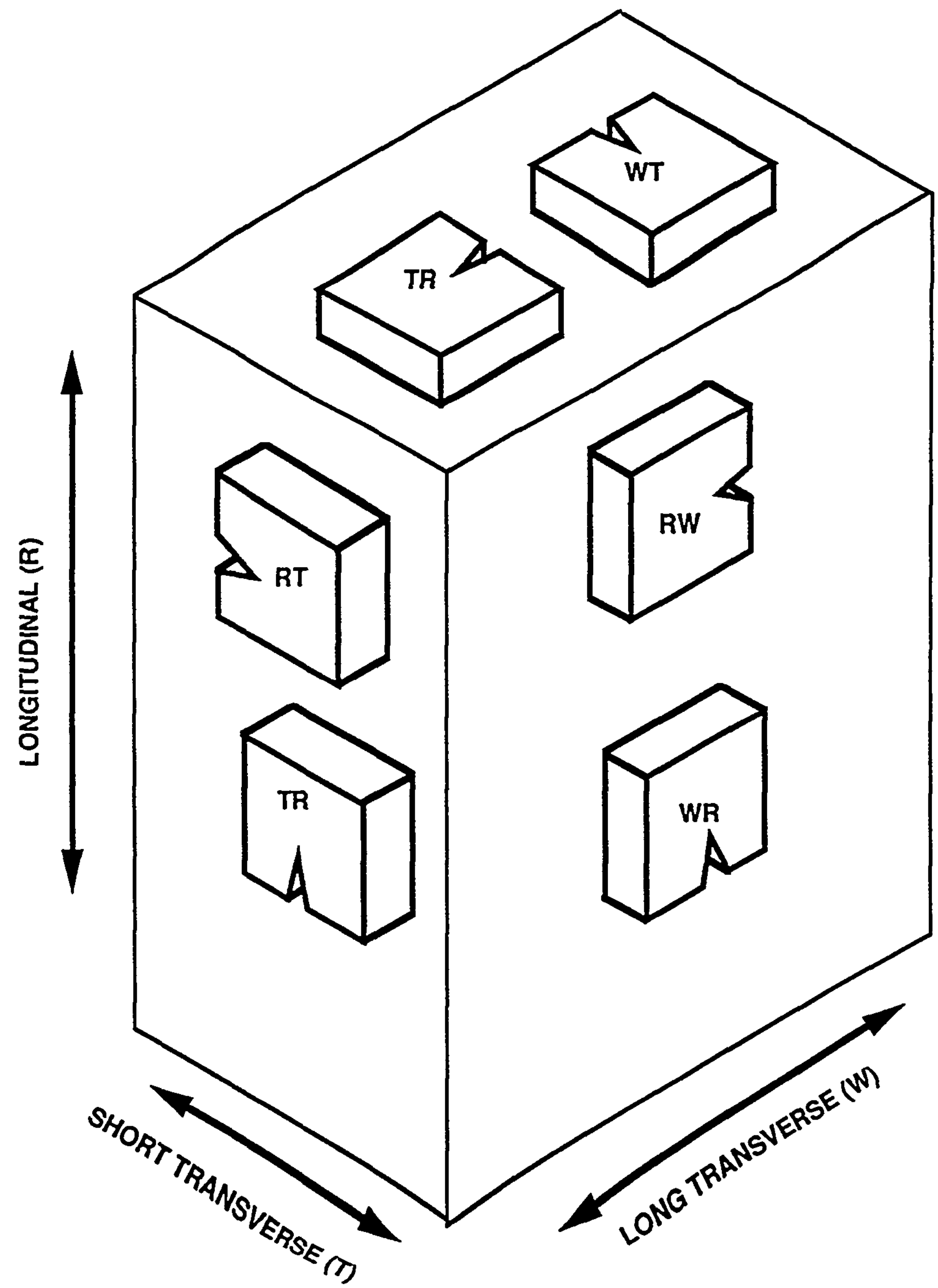

FIG. 2. CRACK ORIENTATIONS IN FORGINGS.

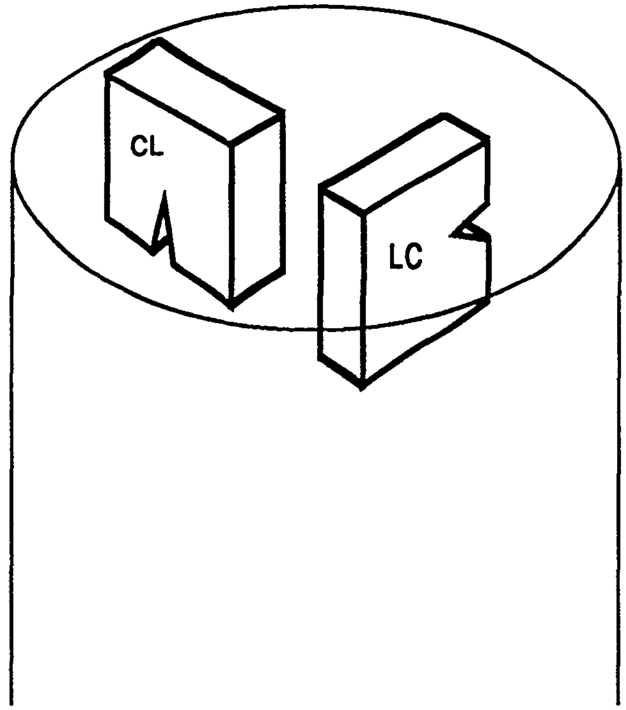

FIG. 3. CRACK ORIENTATIONS IN ROUND BARS.