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TENSILE PROPERTIES OF NEUTRON-IRRADIATED 6061 ALUMINUM ALLOY IN ANNEALED AND PRECIPITATION-HARDENED CONDITIONS

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SUMMARY

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Tensile specimens of 6061 aluminum alloy (nominally 1 wt % Mg, 0.6 Si) were heat treated to give fully annealed ("O" temper) and precipitation-hardened ("T6" temper) conditions and were irradiated in water at 328 K ($0.35 T_m$) to fast (> 0.1 MeV) fluences up to 1.8×10^{27} n/m² and thermal (< 0.025 eV) fluences up to 3.0×10^{27} n/m². The corresponding maximum displacement level was 260 dpa, and over 7 wt % Si was created from transmutation reactions. The major microstructural defects were voids, dislocations and a precipitate of silicon. Swelling from voids was less than 1%. In the "T6" material tested at 323 K ($0.35 T_m$) and 373 K ($0.4 T_m$) irradiation raised the 0.2% flow stress and the UTS by 45 to 60% from the unirradiated values of about 280 and 330 MPa, respectively; ductility was reduced from 15 to about 9%. At 423 K ($0.45 T_m$) there was a similar degree of hardening, but ductility fell to about 5%. The alloy in the "O" condition was softer, by 125 to 150 MPa, than the irradiated "T6" alloy, and its elongation remained above 10%. In all cases the loss in ductility occurred principally through reduction in uniform strain. Fractures were ductile.

KEY WORDS: Aluminum alloy, neutron irradiation, high fluence, voids, transmutation-produced silicon, tensile tests, strengthening, ductility loss.

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TENSILE PROPERTIES OF NEUTRON-IRRADIATED 6061 ALUMINUM ALLOY
IN ANNEALED AND PRECIPITATION-HARDENED CONDITIONS*

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The 6061 aluminum alloy has a nominal composition of 1.0 wt % Mg and 0.6% Si with smaller quantities of Cu and Cr. By suitable quenching and aging a fine precipitate of Mg_2Si can be developed which imparts high strength to the alloy while still retaining adequate ductility. In this "T," or tempered, condition the alloy finds applications in some water-cooled reactors and has been found to provide exceptionally good service [1,2]. The effects of neutron irradiation on 6061 alloy have been summarized by King et al. [1], and detailed microstructural and mechanical property changes in heavily irradiated components from the Oak Ridge High Flux Isotope Reactor (HFIR) have been reported by King et al. [1] and by Farrell and Richt [2]. The damage structure consists of dislocations, a precipitate of transmutation-produced silicon, and some voids, all of which contribute to a strengthening of the alloy and an associated loss in ductility. The alloy in the T6 condition has received the greatest attention. In the "O," or annealed condition, the fine Mg_2Si precipitate is absent and the material is correspondingly weaker but more ductile. There are potential applications for "O" material such as in fuel cladding where higher ductility

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rather than high strength is a prime requirement. Material in the "0" condition has never been subjected to high neutron doses. Therefore, in our studies of neutron damage in aluminum alloys we included 6061 alloy in both "T6" and "0" conditions. This paper describes the changes in tensile properties after high levels of neutron irradiation.

Experimental Conditions

The chemical composition of the alloy was 0.87 wt % Mg, 0.58 Si, 0.18 Cr, 0.37 Cu, 0.27 Fe, 0.015 Mn, and 0.02 Ni. Button-headed tensile specimens of gage length 28.6 mm and gage diameter 3.2 mm were machined from cold-swaged bars and were heat treated as follows:

"0" temper — 2 h at 688 K, cooled at 30 K/h to 530 K, then air cooled to room temperature.

"T6" temper — 1 h at 795 K followed by a water quench, then aged 18 h at 433 K and air cooled.

The heat-treated specimens were irradiated in the peripheral target positions in HFIR in contact with the cooling water at about 328 K ($0.35 T_m$) for periods up to $3\frac{1}{2}$ y during which they accumulated fast ($E > 0.1$ MeV) neutron fluences up to 1.8×10^{27} n/m² and thermal ($E < 0.025$ eV) fluences up to 3.0×10^{27} n/m². The maximum damage level, calculated using the appropriate cross section for the HFIR spectrum and an effective threshold displacement energy of 25 eV, was 260 dpa. The maximum silicon level generated from Al(n, γ) reactions [3] was estimated to be 6.9 at. % (7.15 wt %). Helium and hydrogen concentrations from Al(n, α) and Al(n,p) reactions are estimated to be 8.5×10^{-3} and about 5×10^{-2} at. %, respectively. The "0" specimens were irradiated to fluences about one-third lower than the "T6" specimens. After irradiation, the specimens

were tensile tested to failure at a strain rate of 3×10^{-4} /s at temperatures of 323, 373, and 423 K (0.35, 0.40, and 0.45 T_m) for the "T6" specimens, and 323 and 423 K for the "0" specimens.

Results

Changes in the shapes of tensile curves of the "T6" specimens with increasing fluence are shown in Fig. 1, and the fluence dependencies of the tensile properties at the three test temperatures are illustrated in Figs. 2-4. Note that tensile curves in Fig. 1 and the abscissae in Figs. 2-4 are labelled in terms of the fast fluence. This fluence alone does not determine the mechanical property changes; the thermal fluence makes a significant contribution via the silicon precipitate. The levels of transmutation-produced silicon are indicated on separate scales in Figs. 2-4. At 323 and 373 K radiation raised the 0.2% flow stress and the UTS by 45 to 60% from the unirradiated values of about 280 and 330 MPa, respectively. Correspondingly, the total elongation was reduced from about 15 to 8-9%, almost all of this loss being attributable to a loss in uniform strain at fluences between 10^{25} and 10^{26} n/m², thereafter remaining at a constant level independent of fluence. At 423 K a similar degree of hardening was observed but the ductility loss was more severe, the total elongation falling from 18 to about 5%. Here, the reduction in uniform elongation was very marked. Most of the retained ductility at 423 K occurred in the necked region of the specimens. The fracture mode in the "T6" specimens at all test temperatures did not change with fluence and appeared to be one of ductile tearing.

Examples of tensile curves for the "0" specimens, and the dependence of tensile properties on neutron fluence, are given in Figs. 5-7. The un-irradiated "0" specimen tested at 423 K showed mild serrated flow; neutron irradiation removed all evidence of such serrations. Although the fractional increase in radiation strengthening in the "0" specimens was greater than in the "T6" specimens, the actual strength level attained at a given fluence was lower by 125 to 150 MPa. This is primarily because the "0" specimens were at least that much softer to begin with. At 423 K, the rate of increase in strength with fluence was somewhat higher than in the "T6" specimens. The ductility of the "0" specimens showed a continuous decline with fluence with no signs of saturation being approached except, perhaps, at 423 K (Fig. 7). As with the "T6" specimens, most of the loss in total elongation occurred through loss in uniform strain. Nevertheless, the ductility of the "0" material at a fluence of 10^{27} n/m² was above 10%, and at lesser fluences was substantially better than that for the "T6" condition, especially at 423 K where it was twice as high.

The microstructures of the most heavily irradiated specimens were examined by transmission electron microscopy. In both the "T6" and the "0" materials the dominant feature of the microstructures was a precipitate of transmutation-produced silicon (Fig. 8). In both cases, the shape of the particles was similar and was irregular, seemingly determined by in-situ coalescence of adjacent particles. Rough counts indicated an average size of about 23 nm and a concentration of about 2×10^{21} /m³ within the grains; on grain boundaries the precipitate was manifest as larger, discontinuous slabs (Fig. 8a). In the "T6" specimen the original Mg₂Si

precipitate was retained but was difficult to see directly; it was most easily discernible in diffraction patterns. Rounded voids were also present in low concentration in both materials. These voids displayed identical characteristics to the silicon-coated voids found and analyzed in 1100 aluminum irradiated under these same conditions [4,5], and are assumed to be similarly coated. In the "T6" material irradiated to a fast fluence of 1.8×10^{27} n/m², the void concentration was $\sim 5 \times 10^{19}$ /m³ of average diameter 52 nm and with uniform distribution. In the most heavily irradiated "0" specimen (1.2×10^{27} n/m², >0.1 MeV), the void concentration within the grains was about the same as in the "T6" material, but the average size was greater, about 69 nm, even though the fluence was less than that for the "T6" condition. Moreover, in the "0" material partial sheets of voids were formed alongside some, but by no means all, grain boundaries. Both materials contained dislocations but the structures were too messy to permit measurement of reliable dislocation concentrations. At grain boundaries, the damage-denuded regions were about 30 nm wide.

Discussion and Conclusions

The microstructural features introduced by irradiation are essentially the same as those reported earlier in 6061 aluminum [1,2], with the difference that the voids are now recognized as being coated with silicon. The voids are larger in 6061-0 than in 6061-T6 and the swelling from voids is greater in the "0" material. From the void measurements made on the highest fluence specimens, we calculate the void swelling to be 0.34% for "T6" and 0.8% for "0." These are considerably less than the 6 to 9% void swelling measured in annealed, commercially pure aluminum irradiated

in this same aluminum surveillance program [5]. The transmutation-produced silicon, which is less dense than aluminum, also causes some swelling, estimated to be 1.14% for the "T6" specimen and 0.74% for the "O" specimen.

In earlier papers [1,2,6,7] on radiation-induced mechanical property changes in aluminum components from thermal reactors, and in ref. 5, it has been argued extensively and quantitatively that the increases in strength are adequately explained in terms of dispersion hardening by the microstructural defects. We believe this to hold in the present work, too, and rather than repeat the arguments we refer the reader to the previous work. Similarly, the loss in ductility which appears to follow the classical pattern of lower ductility with increasing dispersed phase, is caused by changes in work-hardening parameters. There was no evidence of low-ductility intergranular failure of the type seen in 1100-0 aluminum [5] and in a 6061-T6 HFIR component [2].

In summary, the 6061 aluminum alloy in annealed ("O") and precipitation-hardened ("T6") conditions appears to be capable of withstanding very high neutron exposures in a water-cooled reactor environment without grievous impairment of mechanical properties and with very good resistance to swelling. The alloy suffers moderate radiation strengthening but retains satisfactory ductility. In the "O" condition the swelling resistance is less than in the "T6" condition but is still very good. The "O" material remains softer and more ductile than the "T6" material because it starts out that way. This carryover of an inherent balance between strength and ductility suggests that there may be some advantage to be gained from tailoring the mechanical strength of the alloy to the minimum required for its service application, with a consequent gain in initial ductility. The alloy will

harden in reactor, and some of the original ductility gain will be carried through the service life, providing an extra margin against failure.

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Fig 1

Fig. 1. Changes in Shapes of Tensile Curves of 6061 Alloy in Originally Precipitation-Hardened (T6) Condition at Various Neutron Fluences. The fast fluence is indicated, and the thermal-to-fast fluence ratio is 1.66.

Fig 2

Fig. 2. Fluence Dependence of Tensile Properties of 6061-T6 at 323 K.

ORNL-DWG 76-3734R

Fig 3

Fig. 3. Fluence Dependence of Tensile Properties of 6061-T6 at 373 K.

ORNL-DWG 76-3735R

Fig 4

Fig. 4. Fluence Dependence of Tensile Properties of 6061-T6 at 423 K.

ORNL-DWG 76-3736R

Fig 5

Fig. 5. Effects of Neutron Irradiation on Tensile Curves of 6061 Alloy Originally in Annealed (0) Condition. The fast fluence is indicated, and the thermal-to-fast fluence ratio is 1.7.

Fig 6

Fig. 6. Fluence Dependence of Tensile Properties of 6061-0 at 323 K.

ORNL-DWG 76-3739R

Fig 7

Fig. 7. Fluence Dependence of Tensile Properties of 6061-0 at 423 K.

ORNL-DWG 76-3740R

B 39217

YE 11593

12K

B 41469

YE 11594

80K

Fig. 8. Microstructures of (a) 6061-T6 after Irradiation to $1.8 \times 10^{27} \text{ n/m}^2$ ($E > 0.1 \text{ MeV}$) and $3.0 \times 10^{27} \text{ n/m}^2$ ($E < 0.025$) at 328 K, (b) 6061-0 after irradiation to $1.2 \times 10^{23} \text{ n/m}^2$ ($E > 0.1 \text{ MeV}$) and $1.9 \times 10^{27} \text{ n/m}^2$ ($E < 0.025$) at 328 K.