# CORRELATION BETWEEN SHEAR PUNCH AND TENSILE DATA FOR NEUTRON-IRRADIATED ALUMINUM ALLOYS

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## OBJECTIVE

This work was performed to determine whether shear punch and tensile data obtained on neutron irradiated aluminum alloys exhibited the same type of relationship as had been seen in other work and to assess the validity of extrapolating the results to proton-irradiated alloys. This work was also meant to be the first of a series of similar test matrices designed to determine whether the shear punch/tensile relationship varied or was the same for different alloy classes.

## SUMMARY

Tensile specimens and TEM disks of two aluminum alloys in two tempers were irradiated at 90-120°C with neutrons from spallation reactions in the Los Alamos Spallation Radiation Effects Facility (LASREF) at the Los Alamos Meson Physics Facility (LAMPF). The materials were exposed to a fluence of 3.4-4 x $10^{20}$ n/cm$^2$. This work was part of a study to determine the potential for using aluminum alloys as structural components in accelerators used to produce tritium. Shear punch tests and tensile tests were performed at room temperature and at 100°C, a temperature characteristic of the operating temperature in the application of interest. Shear punch and tensile data from unirradiated specimens were used to develop a correlation between shear punch and tensile strengths. Using the shear punch data from the neutron irradiated TEM disks, the correlation predicted the tensile strength of the neutron irradiated condition reasonably well. Shear punch data on similar 760 MeV proton-irradiated specimens were used with the correlation in an attempt to predict uniaxial strength in the proton irradiated condition.

## PROGRESS AND STATUS

### Introduction

Aluminum alloys are being considered for blanket and target structural applications in the Accelerator Production of Tritium (APT) Program at Los Alamos National Laboratory (LANL). The irradiation environment will consist of both high energy protons and neutrons as well as a large number of neutrons over a range of energies below the initial spallation neutron energy spectrum. Aluminum alloys were selected because of their low absorption of thermal neutrons, their high thermal conductivity, their fabricability and joinability, their performance under prototypic and other irradiation conditions, and their low activation under such conditions.

Irradiation performance data for materials in such an environment are extremely limited. Miniature tensile specimens and transmission electron microscopy (TEM) disks that were previously irradiated with neutrons or protons were available for the alloys of interest, however, which eliminated the time typically required for materials irradiation prior to testing. Both tensile specimens and TEM disks were available for the

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neutron irradiated condition, while only TEM disks were available for the proton irradiated condition. The alloys available were 6061, in both an annealed (O) and precipitation strengthened (T6) condition, and a German version of 5052, also in an annealed (O) and in a strengthened (similar to H38) condition. While this material is slightly different in composition than that specified in Reference 1, it is referred to in this work as alloy 5052 for simplicity.

The specimens were irradiated in LASREF at the Los Alamos Meson Physics Facility (LAMPF), exposing the materials of interest to either medium energy protons or spallation neutrons. Irradiation in the neutron flux proceeded at temperatures ranging from 90 to 120°C. The neutron dose achieved was 3.4-4 x $10^{20}$ n/cm$^2$ with about 1% of the neutrons having E > 1 MeV. The proton irradiation was conducted at temperatures estimated by calculation to be 200-300°C. The proton dose on these samples reached 2-3 x $10^{20}$ p/cm$^2$ with a proton energy of about 760 MeV.

Mechanical properties data for irradiations under these types of irradiation conditions are extremely limited. The most cost effective use of irradiated test specimens allows the extraction of as much data as possible from the fewest number of specimens. This becomes particularly significant when materials irradiations are performed in small volumes. Miniature tensile specimens have been used for many years, but the use of even smaller specimens to generate tensile data has been considered by many researchers. The shear punch test is one such test that was developed a number of years ago as a technique for extracting strength and ductility information from TEM disks.[2] It utilizes a cylindrical punch with a flat end to deform a lightly clamped disk to failure. The disk material is forced to deform primarily in a small region corresponding roughly to the region below the clearance between the punch and die. It has been found empirically that the yield and maximum loads can be correlated with the uniaxial yield and ultimate stresses, respectively, and that the displacement at failure can be related to uniaxial reduction in area.

Since both neutron irradiated tensile specimens and neutron irradiated TEM disks were available, the current test program was seen as an opportunity to further develop the relationship between tensile and shear punch behavior, and to use this relationship to try to predict the tensile behavior of proton irradiated material from the shear punch behavior of proton irradiated disks. A sufficient number of unirradiated specimens existed to establish a correlation between shear punch and tensile strength for the unirradiated condition. The tensile strength predicted by the correlation for the neutron irradiated condition on the basis of the shear punch data obtained on neutron irradiated TEM disks was compared to the actual tensile properties obtained on neutron irradiated tensile specimens. Assuming that the neutron irradiated data would be consistent with the correlation developed on unirradiated material, then the correlation would be used to predict the tensile properties of the proton irradiated conditions from the shear punch data obtained in the same conditions.

While the specific alloys considered in this particular project were of interest to LANL, and while partial financial support for this work was provided by LANL, the shear punch/tensile correlation work itself is being investigated due its potential for application within the fusion materials program. The development of miniature specimens will be of particular importance to the fusion materials program when an advanced neutron source is built for the simulation of fusion neutrons. Such a device will have only a very limited volume for the irradiation of materials specimens, and existing tensile specimens are quite large relative to the TEM disk used for the shear punch test. Thus the data obtained in this effort will be used in the evaluation of the shear punch test as a viable means of extracting tensile data from TEM disks.

## Experimental Procedure

**Shear Punch Testing.** Shear punch tests were performed at both room temperature and 100°C (±2°C). Room temperature tests were performed to facilitate comparison to data available on these alloys after irradiation in mixed spectrum fission reactors. Tests at 100°C were selected as being representative of the expected operating temperature in APT structural elements as well as being representative of the irradiation temperature. Punch tests were performed in a screw-driven Instron test machine at a crosshead speed of 0.127 mm/min (0.005 in./min). Room temperature tests were performed in air. Elevated temperature was achieved by resistance heating in an argon-filled, insulated test chamber. Heat-up time was ~30 minutes. Specimen displacement during a test was assumed to be equal to crosshead travel.

Shear punch tests were performed on both unirradiated control specimens and a set of LAMPF-irradiated specimens. Ten tests were done for each of the four unirradiated alloy conditions at both room temperature and 100°C. One or two tests were done for each of the four neutron irradiated alloy conditions at both room temperature and 100°C. One test was done at room temperature for each of the four proton irradiated alloy conditions. The specimens were fabricated by punching, and nominally measured 0.25 mm (0.010 inches) thick and 2.79 mm (0.110 inches) in diameter. All irradiated specimens were flattened prior to shear punch testing in a device that applied a small load to the specimens while they were located in a recessed die. The specimens were flattened to facilitate testing, and no change in dislocation structure was anticipated as a result of the flattening operation. The unirradiated specimens were not flattened.

Specimen thicknesses were measured using a calibrated dial micrometer with a rounded contact, attached to a flat anvil. Specimen thickness was measured at least six times in different places on each specimen to verify that the three measurements recorded were representative. Shims of the appropriate thickness were placed between the two fixture halves to control the spacing between the two to be a fraction of a mil less than the specimen thickness. The specimen was placed over the blanking hole in the lower fixture with the deburred (i.e., cupped) side of the specimen facing up to ensure good specimen/die and specimen/punch contact. The upper fixture was placed on top of the assembly and the bolts holding it in place were tightened while the upper and lower fixture alignment was maintained. A push pin 1.00 mm (0.0395 inches) in diameter was used to punch the specimens. The guide hole for the push pin consisted of a bushing with a 1.02 mm (0.0400 inch) inner diameter in the upper half of the fixture. A bushing with a 1.04 mm (0.0410 inch) inner diameter formed the die hole in the lower half of the fixture.

**Uniaxial Tensile Testing.** Uniaxial tensile tests were performed on both unirradiated control specimens and a set of LAMPF-irradiated specimens. Ten tests were done for each of the four unirradiated alloy conditions at both room temperature and 100°C. Two tests were done for each of the four neutron irradiated alloy conditions at both room temperature and 100°C. The specimens were sheet specimens measuring nominally 0.25 mm (0.010 in.) in thickness, 18 mm (0.710 in.) in gauge length, and 3 mm (0.120 in.) in gauge width. Tensile properties were measured using a standard hydraulic tensile frame with an extension rate of 0.1 mm/m. The elevated temperature tests were carried out in a heated air furnace chamber where the specimen was brought to uniform temperature in ~10 minutes. Displacement was controlled by an LVDT attached to a hydraulic piston, and load was monitored with a standard load cell. Other details of the tensile tests and a discussion of the results are described elsewhere in this proceedings.[3]

## Results and Discussion

**Shear Punch Data.** The average strengths determined from the tensile and shear punch tests are given in Table 1. The tensile data are described in more detail in Reference 3. The shear punch strengths were determined for both yield and maximum conditions according to $\tau = \frac{P}{2\pi r t}$, where $\tau$ is the shear stress,

**Table 1.** Average shear punch and tensile data

| MATERIAL | YIELD STRENGTH (MPa) | | | MAXIMUM STRENGTH (MPa) | | |
|---|---|---|---|---|---|---|
| | UNIRR[a] | N IRR[b] | P IRR[b] | UNIRR[a] | N IRR[b] | P IRR[b] |
| Shear punch, room temperature | | | | | | |
| 6061-O | 44 ± 4[c] | -[d] | 35 | 91 ± 2 | - | 89 |
| 6061-T6 | 131 ± 5 | 140 | 29 | 188 ± 3 | 193 | 88 |
| 5052-O | 71 ± 6 | 62 | 73 | 142 ± 3 | 139 | 145 |
| 5052-H38 | 136 ± 4 | 119 | 45 | 180 ± 3 | 182 | 141 |
| Shear punch, 100°C | | | | | | |
| 6061-O | 45 ± 3 | - | - | 90 ± 2 | - | - |
| 6061-T6 | 122 ± 6 | 135 ± 0 | - | 182 ± 3 | 187 ± 2 | - |
| 5052-O | 83 ± 3 | 70 ± 6 | - | 146 ± 2 | 148 ± 3 | - |
| 5052-H38 | 137 ± 7 | 127 ± 5 | - | 178 ± 3 | 179 ± 0 | - |
| Tensile, room temperature[(3)] | | | | | | |
| 6061-O | 49 | 54 | - | 128 | 147 | - |
| 6061-T6 | 233 | 244 | - | 311 | 305 | - |
| 5052-O | 96 | 101 | - | 208 | 213 | - |
| 5052-H38 | 301 | 264 | - | 335 | 320 | - |
| Tensile, 100°C[(3)] | | | | | | |
| 6061-O | 62 | 63 | - | 129 | 137 | - |
| 6061-T6 | 259 | 221 | - | 305 | 287 | - |
| 5052-O | 104 | 113 | - | 215 | 221 | - |
| 5052-H38 | 285 | 259 | - | 315 | 318 | - |

[a]8-10 tests per condition
[b]One test per condition
[c]Standard deviation
[d]Indicates no test performed or test data invalid

P is the load, t is the average specimen thickness, and r is an effective radius defined as the average of the punch and blanking radii, or 20.16 mils for the push pin used for these tests. The load value for the yield condition was determined at the point where the load-displacement trace deviated from linearity. Standard deviations are given only for those conditions where two or more specimens were tested. Note that the shear punch test produces a stress state that is not pure shear, and the shear punch strengths cannot truly be considered to be shear yield and shear maximum strengths.[2] This terminology will be used, however, for the sake of simplicity.

The average shear punch data are shown in Figures 1 and 2 versus the average tensile data that are given in Table 1. The data clustered in the lower left quadrant of these two figures were obtained on the annealed alloys, while the data clustered in the upper right quadrant were obtained on the strengthened alloys. The data appear to cluster fairly linearly, consistent with earlier work on shear punch testing.[2] The difference between properties observed at room temperature and at 100°C was slight, indicating that the microstructure is reasonably stable at 100°C, at least for short periods of time. Only minor changes in shear punch or tensile strength were observed following neutron irradiation.

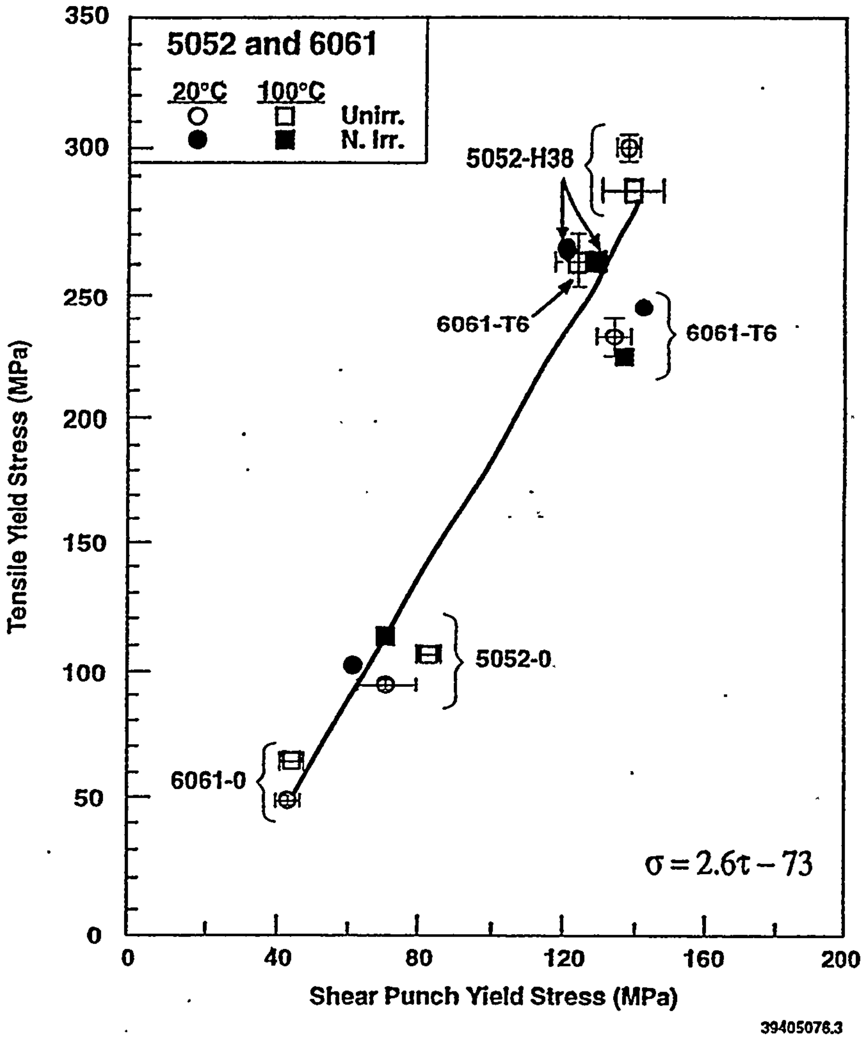


Figure 1. Average tensile yield versus shear yield strength for unirradiated and neutron irradiated alloys 5052 and 6061, with the regression line for the data from unirradiated specimens.

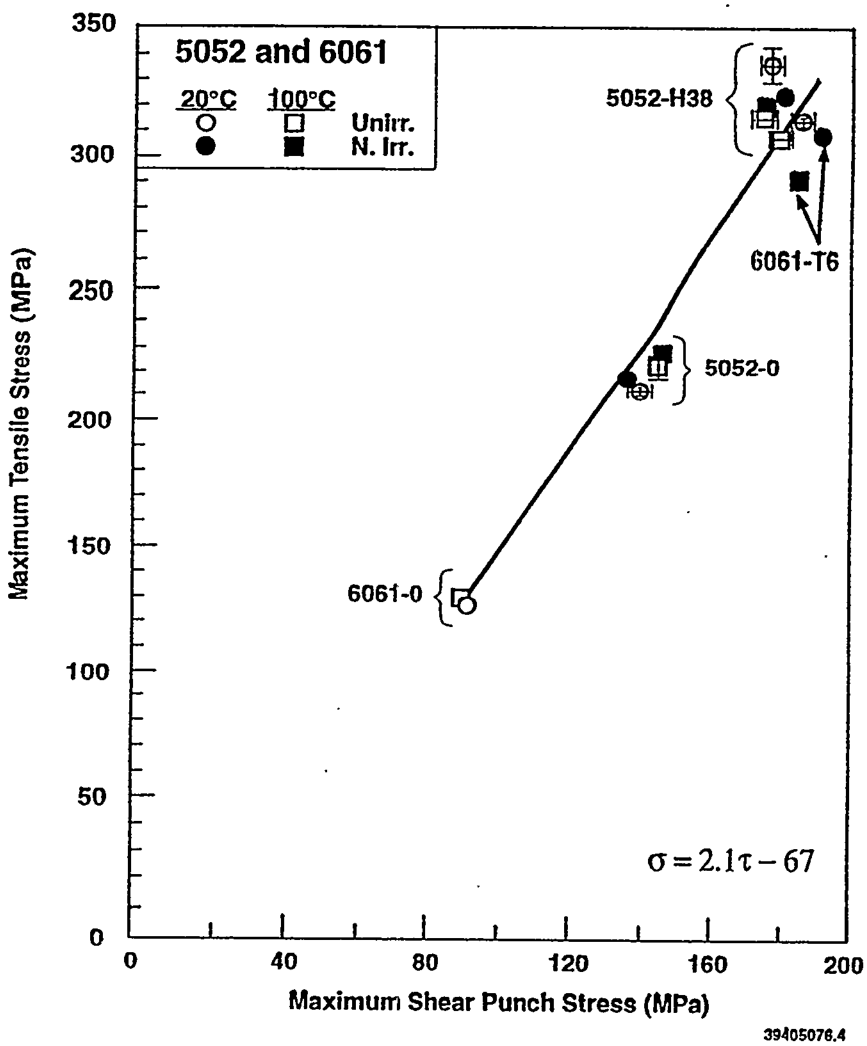


Figure 2. Average tensile maximum versus shear maximum strength for unirradiated and neutron irradiated alloys 5052 and 6061, with the regression line for the data from unirradiated specimens.

Inspection of the data in Table 1 reveals that there are some anomalies in both the tensile and shear data. First is the fact that the strength observed at 100°C is sometimes greater than that observed at room temperature. This is evident in both the tensile and the shear data for several different test conditions. While Reference 4 indicates that the yield and maximum strengths of these alloys typically decrease slightly as the temperature is increased from 20 to 100°C, other researchers have also observed an increase in strength over this temperature range.[5] Only the 5052 load-displacement traces, however, exhibited the serrations typical of dynamic strain aging.

While very little change in strength was observed following neutron irradiation (the largest shift was by 38 MPa; the majority of alloy conditions shifted by less than 20 MPa), significant strength changes were observed in the strengthened alloys following proton irradiation. The strength of the annealed alloys remained essentially the same after proton irradiation, but the hardened alloys softened significantly. The yield and maximum strength of the precipitation strengthened 6061 decreased down to values effectively the same as those exhibited in the annealed condition. These results are consistent with a loss of strengthening due to the dissolution of the $Mg_2Si$ precipitates during the exposure to 760 MeV protons.

While the maximum strength of the strengthened 5052 also decreased to that of the annealed material, the yield strength decreased much more, to a value well below that observed in the annealed condition. This softening is most likely due to the recovery of the cold work dislocation structure at elevated temperature, accelerated by radiation enhanced diffusion. More discussion of these phenomena is given in Reference 1.

**Correlation Development.** The data given in Table 1 were used to develop a correlation relating the shear punch to the tensile data. The averaged shear data were weighted in the correlations according to the number of data points used to calculate the shear strength averages. Regression lines are of the form $\sigma = C\tau + K$ were fit to the data, where $\sigma$ is the uniaxial tensile stress and $\tau$ is the shear stress. The constant K was allowed to vary since the data do not appear in Figures 1 and 2 to lie on a line that goes through the origin.

Since there is no apparent distinction between the data obtained at room temperature and 100°C, all the data obtained in the unirradiated condition was used to generate the following equations for the yield and maximum load conditions, respectively:

$$\sigma_y = 2.6\tau_y - 73 \qquad \text{and} \qquad \sigma_m = 2.1\tau_m - 67$$

where both $\sigma$ and $\tau$ are in MPa. The $r^2$ values for both of these regressions was 0.98.

The correlations determined by G. E. Lucas were of the form $\tau = m\sigma$, with m = 0:54 and 0.62 for the yield and ultimate conditions, respectively. Thus the values from Lucas' work that are comparable to C are actually 1/m, or 1/0.54 = 1.85 and 1/0.62 = 1.61 for the yield and ultimate conditions, respectively. There is no constant K in Lucas' correlations because the offset from the axis was considered to be a frictional component of the shear stress and was incorporated into the original calculation of shear stress according to $\tau = \frac{P-F}{2\pi rt}$. Lucas' values of C are somewhat different from the values obtained in the current study. This is most likely due to either the way the offset was incorporated or to the fact that, since the original correlations were determined for a combination of data obtained on copper, brass, steel, aluminum and stainless steel alloys, they represent an average of the behavior of all the alloys considered.

Data in Reference 4 suggest that the relationship between shear and tensile strength varies between alloy systems. Figures 3 and 4 show maximum shear and tensile strength data obtained on full size specimens of a variety of aluminum alloys (Figure 3) and copper-zinc alloys (Figure 4). The aluminum alloys for which data on full size specimens are shown in Figure 3 range from the 1000 to the 7000 series and include alloys strengthened by a number of mechanisms. All the alloys appear to obey the same relationship between shear and tensile strength. The data obtained in the current study on miniature specimens are shown in the same plot. The data on the full size and miniature specimens appear to obey the same relationship despite the fact that the miniature specimens were subjected to the shear punch test and the full size specimens were probably tested in torsion. The data shown in Figure 4 are for copper-zinc alloys ranging from 5 to 40 weight percent zinc. All the data appear to obey the same relationship between shear and tensile strength except for the Cu-40Zn alloy, which is the only alloy in the group for which the zinc level exceeds the limit of solid solubility in Cu. It is worth noting that, while the maximum tensile and shear strengths of many different types of aluminum alloys obey the same relationship, the same is not true for the copper-zinc alloys. It is also worth noting that, counter to what one might expect intuitively, the regression lines fit to the data in Figures 3 and 4 do not intersect the origin.

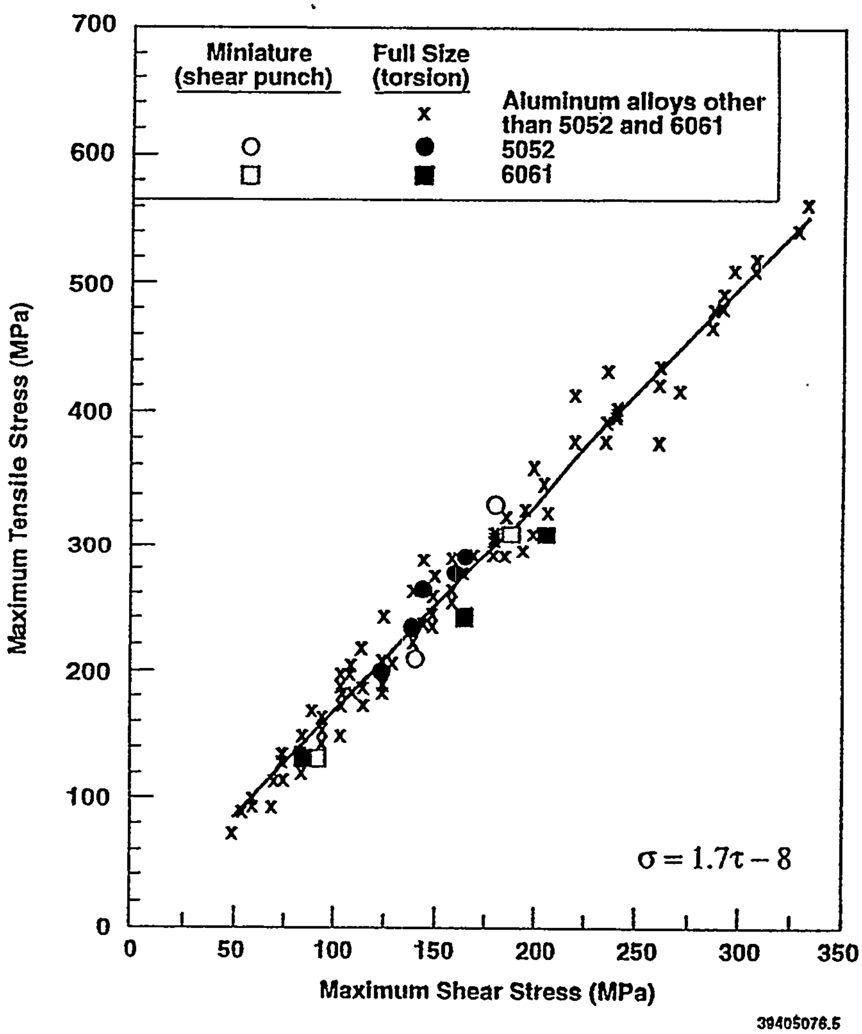


Figure 3. Maximum tensile and maximum shear strength data obtained on full size specimens of a number of aluminum alloys (Reference 4).

The constants C and K are compared in Table 2 for the data sets discussed above. The data are ordered by increasing slope (i.e., increasing value of C). There is a range of values observed for both C and K. It is not known at this time if the range of values is related to the differences between alloy classes, to the number of data points used to generate the correlations, to a difference in the results obtained in tests on full size and miniature specimens, or the degree of shear to which specimens in the shear punch test are subjected (it is assumed that the handbook data on standard specimens was obtained in torsion, or pure shear). It is somewhat counter-intuitive that the value of K is not zero for at least the yield condition; this implies that either the relationship between shear and tensile strengths is nonlinear at the lower values of strength, or that there is some threshold below which the relationship between the two is simply not valid. Clearly a large negative value of the intercept K will dominate any prediction of tensile strength when a low shear strength is obtained.

**Table 2.** Regression constants for $\sigma_m = C\tau_m + K$, where $\sigma_m$ and $\tau_m$ denote the maximum strengths.

| Alloy | Test temp. (°C) | Specimen size | Test type | No. of data points | C | K |
|---|---|---|---|---|---|---|
| Steel, aluminum, copper, stainless steel, brass | RT[a] | Miniature | Shear punch | 24 | 1.6 | - |
| Various aluminum | RT | Full | Torsion[b] | 126 | 1.7 | -8 |
| 6061 + 5052 aluminum | RT, 100 | Miniature | Shear punch | 8 | 2.1 | -67 |
| Various copper-zinc (up through 35% zinc) | RT | Full | Torsion[b] | 72 | 2.9 | -335 |

[a]RT = room temperature
[b]It is assumed that the data from Reference 4 were obtained on standard, full size specimens in torsion; this information was not specified.

*Proton irradiated condition.* Since the correlation that was developed on the basis of the data from unirradiated specimens seemed to make reasonable predictions of the tensile strength observed in the neutron irradiated specimens, the correlation was applied to the shear punch data on proton irradiated specimens to predict the tensile strength of the proton irradiated condition. The tensile values calculated for the proton irradiated condition are shown in Table 4. Since no tensile data are available for comparison, no firm conclusions can be drawn on the basis of these results about the applicability of any of the correlations to the proton irradiated aluminum alloys. Several observations related to the predictions are pertinent, however.

The good agreement observed in the neutron irradiated condition between the ultimate tensile strength and the predicted values suggests that the predicted values of ultimate tensile strength for the proton irradiated condition could be considered quantitatively. The yield strength predictions, however, seem suspect, particularly since two out of the four values are quite low. The shear yield strength in all alloy conditions following proton irradiation is generally the same as or lower than the shear yield strength of the corresponding alloy in the unirradiated annealed condition. Thus it is reasonable that the predicted tensile strengths follow a similar trend. The stress ranges observed in the shear punch tests on proton irradiated specimens were either well below or only marginally overlapped the values obtained in tests on specimens in the other conditions. The validity of extrapolating the correlations to these stress ranges is therefore somewhat questionable.

CONCLUSIONS

Neutron irradiation at 90-120°C caused only minor changes in the strength of annealed and strengthened aluminum alloys 6061 and 5052 at a fluence of ~3 x $10^{20}$ n/cm$^2$. Irradiation with 760 MeV protons at 200-300°C to ~3 x $10^{20}$ p/cm$^2$, however, produced a significant decrease in strength in the strengthened alloy conditions. A correlation was developed using the data from unirradiated specimens that describes the relationship between the shear and uniaxial yield and maximum strengths. The uniaxial data obtained

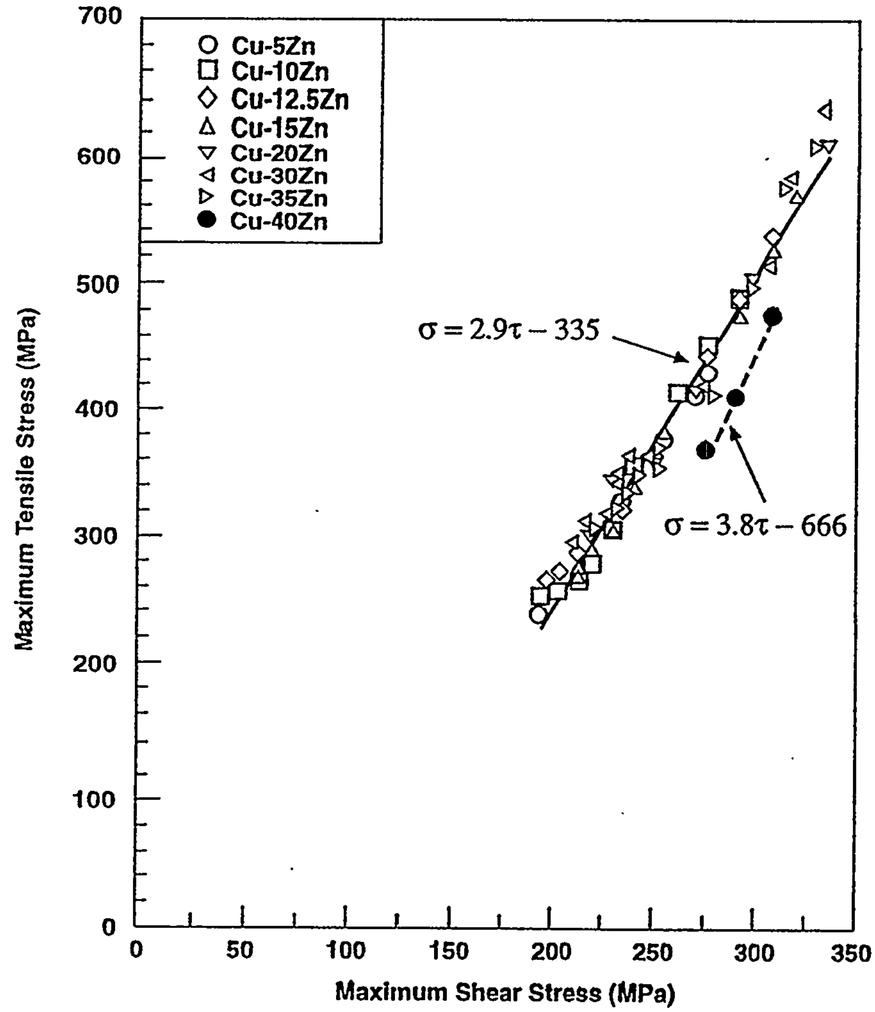


Figure 4. Maximum tensile and maximum shear strength data obtained on full size specimens of a number of copper alloys (Reference 4).

**Correlation Predictions.**

*Neutron irradiated condition.* The tensile values calculated on the basis of the neutron irradiated shear punch data, using the correlations determined from the unirradiated shear punch data, are shown in Table 3 along with the tensile data obtained on neutron irradiated tensile specimens. The predictions of the correlation developed for the unirradiated data from Reference 4 on full size specimens (Table 2) are included since the miniature specimen data appeared to overlap the full size specimen data quite well. The ultimate strength (UTS) predictions are typically within about 10% of the actual tensile values obtained regardless of which correlation was used. The yield strength (YS) predictions were slightly less accurate. The implication is that the data on miniature specimens of the two aluminum alloys can be considered part of a larger group that includes data on full size specimens of many aluminum alloys.

**Table 3.** Correlation predictions of tensile properties for neutron irradiated aluminum alloys

| SPECIMEN DESCRIPTION | | TENSILE VALUES (MPa) | | | |
|---|---|---|---|---|---|
| | | PREDICTED* | | ACTUAL | |
| ALLOY | TEST TEMP (°C) | YS (% error) | UTS (% error) | YS | UTS |
| 6061-T6 | 20 | 291 (19) | 333 (9)<br>320 (5) | 244 | 305 |
| | 100 | 278 (26) | 320 (11)<br>310 (8) | 221 | 287 |
| 5052-O | 20 | 88 (-13) | 221 (4)<br>228 (7) | 101 | 213 |
| | 100 | 109 (-4) | 240 (9)<br>244 (10) | 113 | 221 |
| 5052-H38 | 20 | 236 (-10) | 310 (-3)<br>301 (-6) | 264 | 320 |
| | 100 | 257 (-1) | 304 (-4)<br>296 (-7) | 259 | 318 |

*The first line in each row represents the prediction of the correlation developed on the basis of the unirradiated shear punch data. The second line in the UTS column represents the prediction of the correlation developed on the basis of the data from Reference 4 on full size specimens.

on the neutron irradiated specimens was in reasonable agreement with the predictions of the correlation calculated using the shear punch data for the neutron irradiated condition. While the correlation predictions for the maximum uniaxial strength in the proton irradiated condition appear to be valid, the uniaxial yield strength predictions are somewhat suspect.

## FUTURE WORK

Shear punch and tensile tests will be done on alloys in several different materials classes to determine whether a linear relationship exists between shear and tensile strengths for these classes of alloys, and whether such a relationship varies with alloy class. The materials for which tests are currently planned include a variety of steels as well as copper and vanadium alloys. In addition, similar tests will be performed on irradiated specimens if it is determined that such a relationship exists for unirradiated materials, to ascertain whether the same relationship holds for irradiated materials behavior.

**Table 4.** Shear strength changes and predicted tensile strength changes at room temperature with proton irradiation.

| ALLOY | SHEAR PUNCH TEST | | TENSILE TEST | |
|---|---|---|---|---|
| | UNIRR | P IRR | UNIRR | PREDICTED FOR PROTON IRRADIATION |
| YIELD STRENGTH (MPa) | | | | |
| 6061-O | 44 ± 4 | 35 | 49 | 18 |
| 6061-T6 | 131 ± 5 | 29 | 233 | 2 |
| 5052-O | 71 ± 6 | 73 | 96 | 117 |
| 5052-H38 | 136 ± 4 | 45 | 301 | 44 |
| MAXIMUM STRENGTH (MPa) | | | | |
| 6061-O | 91 ± 2 | 89 | 128 | 120 |
| 6061-T6 | 188 ± 3 | 88 | 311 | 118 |
| 5052-O | 142 ± 3 | 145 | 208 | 238 |
| 5052-H38 | 180 ± 3 | 141 | 335 | 229 |

REFERENCES


1. APT Materials Safety Experiments Technical Report, LA-UR-93-2850, September 1993.

2. G. E. Lucas, J. W. Sheckherd, G. R. Odette, "Shear Punch and Microhardness Tests for Strength and Ductility Measurements," ASTM STP 888, American Society for Testing and Materials (1986) pp. 112-140.

3. J. F. Dunlap, J. F. Stubbins, M. J. Borden and W. F. Sommer, "Room and Elevated Temperature Tensile Properties of Aluminum Alloys 6061 and 5052 Following Irradiation with Spallation-Produced Neutrons, this proceedings.

4. Metals Handbook, volume 2, (1990), American Society for Testing Materials.

5. K. Farrell and R. T. King, "Tensile Properties of Neutron-Irradiated 6061 Aluminum Alloy in Annealed and Precipitation-Hardened Conditions," ASTM STP 633, (1979) pp. 440-449.