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# Effect of Cold Work on the Tensile Properties of 6061, 2024, and 7075 Al Alloys

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**Aluminum alloys 6061, 2024, and 7075 were heat treated to various tempers and then subjected to a range of plastic strain (stretching) in order to determine their strain limits. Tensile properties, conductivity, hardness, and grain size measurements were evaluated. The effects of the plastic strain on these properties are discussed and strain limits are suggested.**

**Keywords** Al alloys, mechanical properties, plastic strain, various tempers

## 1. Introduction

Strain hardening occurs during most working and forming operations of aluminum alloys. It is a very common technique in manufacturing and is the desired process in the fabrication of brackets and bent parts. The strain (stretching) that is applied to samples is also a form of cold work. Cold work has a significant effect on the mechanical properties of alloys and predictions can be made concerning the properties if the amount of cold work is known (Ref 1).

In this study, the effect of cold work on the tensile properties of aluminum alloys was evaluated. These alloys include Al 6061, 2024, and 7075. 6061 is an Al-Mg-Si alloy and its tempers include T6 and O; 2024 is an Al-Cu-Mg alloy and its tempers include T3, T8, O, and T62; 7075 is an Al-Zn-Mg-Cu alloy and its tempers include O and T62, (Ref 2, 3).

6061 is an Al-Mg-Si alloy and is widely used as a medium strength structural alloy. It has the advantages of good weldability and corrosion resistance and is used mostly in extrusions. 2024 is an Al-Cu-Mg alloy with high strength and is often used in the T3 and T4 tempers. It has a high response to artificial aging, especially if cold work is applied prior to aging (T8 temper). 7075 is an Al-Zn-Mg-Cu alloy with very high strength and is mostly used in the T6 and T7 tempers (Ref 2).

Stretching a metal before aging will create dislocations, increasing the amount of sites for plate or needle like precipitates. Therefore higher strengths and lower ductility were expected, as the applied strain is increased (Ref 2, 3).

Current handbooks caution about the effect of strain on properties, but no limits are set on the amount of strain. The goal of this study is to determine the specific effect of varying amounts of strain on the tensile properties of three aluminum alloys in different tempers. The properties that are shown by the tests could be helpful in choosing a material when designing different components for engineering applications. In future studies the bending strain will be evaluated and related to uniaxial stretching strain.

## 2. Experimental Procedure

The materials were supplied by AMI Metals and Kaiser Aluminum in the form of three sheets. One was Al 2024-T3 with dimensions 120 × 90 × 0.16 cm (48″ × 35.5″ × 0.063″), another was Al 6061-T6 with dimensions 120 × 113 × 0.16 cm (48″ × 44.5″ × 0.063″), and the last was Al 7075-O with dimensions 120 × 90 × 0.127 cm (948″ × 35″ × 0.05″).

The compositions are shown in Table 1. The published (typical) property values for the various tempers of 2024, 6061 and 7075 are shown in Table 2.

Wide strips of 2.54 cm (one-inch) were sheared from each sheet and cut into 2.5 × 20.3 cm (1″ × 8″) rectangular specimens. These were then machined into tensile specimens. Three samples were made for each of the tempers shown in Table 3. Heat treatments were performed using Thermolyne type 3040 C furnaces and Thermolyne series 9000 ovens.

The size of the tensile bars for the stretching procedure had to be determined. Two additional coupons were machined out of the 2024-T3 sheet: one with the standard 2.54 × 20.3 cm (1″ × 8″) dimensions with a 1.27 × 10 cm (0.5″ × 4″) gage region and one with larger dimensions, 5.1×30.1 cm (2″ × 12″) dimensions with a 2.54 × 20.3 cm (1″ × 8″) wide gage region. Both samples were stretched to approximately 9% elongation using an MTS 810 hydraulic frame and then were heat treated to the T8 condition. The larger sample was then machined to the dimensions of the smaller sample and both were tested using the MTS frame. There was little variation between the two samples, so it was determined that stretching the samples in the standard 2.54 × 20.3 cm (1″ × 8″) size was sufficiently accurate.

Table 3 shows the treatments performed to produce different tempers. After stretching, the samples were heat treated to the

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**Table 1 Chemical composition of 2024, 6061, and 7075 by weight percentages (Ref 4)**

| | Si | Fe | Cu | Mn | Mg | Cr | Zn | Ti | Al |
|---|---|---|---|---|---|---|---|---|---|
| 2024 | 0.50 | 0.50 | 3.8-4.9 | 0.3-0.9 | 1.2-1.8 | 0.10 | 0.25 | 0.15 | 90.75-93.05 |
| 6061 | 0.40-0.8 | 0.7 | 0.15-0.40 | 0.15 | 0.8-1.2 | 0.04-0.35 | 0.25 | 0.15 | 95.85-97.21 |
| 7075 | 0.40 | 0.50 | 1.2-2.0 | 0.30 | 2.1-2.9 | 0.18-0.28 | 5.1-6.1 | 0.20 | 87.17-89.87 |

The published (typical) property values for the various tempers of 2024, 6061, and 7075 are shown in Table 2.

**Table 2 Published values for the aluminum alloys used in this study (Ref 4)**

| | | MPa, ksi | MPa, ksi | % Elong | Conductivity, IACS | Hardness, 15T |
|---|---|---|---|---|---|---|
| 6061 | T6 | 310 (45) | 276 (40) | 5-12 | 43.2 | 80.1 |
| | T62 | 310 (45) | 276 (40) | 5-12 | 43.2 | 80.1 |
| 2024 | T62 | 426.5 (61.9) | 345 (50) | 5-5.8 | 38.4 | 86 |
| | T81 | 484.4 (70.3) | 450 (65.3) | 4-5 | 38.4 | 86.3 |
| | T8 | 484 (70.3) | 450 (65.3) | 4-5 | 38.4 | 86.3 |
| 7075 | T62 | 572 (83) | 503 (73) | 3-9 | 33.2 | 88.9 |
| | T6 | 572 (83) | 503 (73) | 2-10 | 33.5 | 88.9 |

**Table 3 Tempers and treatments (Ref 2)**

| Material | Temper | Heat treatments |
|---|---|---|
| 2024-T3 | Solution heat-treated, cold worked, and naturally aged to a substantially stable condition. | None (as received) |
| 2024-T8 | Solution heat-treated, cold worked, and artificially aged. | Aged: 191 °C (375 °F) for 12-13 h. |
| 2024-O | Annealed wrought condition | Solution heat treat: 404 °C (760 °F) for 2-3 h and furnace cool (slow) |
| 2024-T62 | Solution heat treated from the O or the F temper and artificially aged. | From T3 temper: SHT → Water quench → Natural age (room temp. 96 h.) → Age: 191 C (375 F) for 9-12 h. |
| 6061-T6 | Solution heat-treated and artificially aged. | None (as received) |
| 6061-O | Annealed wrought condition | Solution heat treat: 404 °C (760 °F) for 2-3 h and furnace cool (slow) |
| 7075-O | Annealed wrought condition | None (as received) |
| 7075-T62 | Solution heat treated from the O or the F temper and artificially aged | Solution heat treat: 465 °C (870 °F) for 30 min → Age: 121 C (250 F) for 23-25 h. |

test condition (Table 4). A total of 69 tensile specimen coupons were machined out of the alloy sheets in preparation for testing three samples at each of the 23 conditions of strain percent at different tempers.

Conductivity tests were performed using an Eddy-Current Tester to determine the percent conductivity (International Annealed Copper Standard, IACS). Tensile testing was performed using the MTS 810 frame. Hardness tests were performed on the grip sections of the tensile specimens using a superficial 15T scale.

Three small rectangular pieces were cut from between the gage marks of a sample from each condition. Optical microscopy was performed on each sample. Grain size measurements were measured according to following relation:

$$D = L/PM \qquad \text{(Eq 1)}$$

Where $L$ is the total test-line length, $M$ is the magnification and $P$ is the number of grain boundary intercepts, (Ref 5).

**Table 4 Forming and testing plan**

| | Form | % Strain | Condition |
|---|---|---|---|
| 6061 | T6 | 2,4,6,8 | T6 |
| | O | 4,8,12,16 | T62 |
| 2024 | O | 4,8,12 | T62 |
| | T3 | 3,6,9,12 | T81 |
| | T8 | 2,4 | T8 |
| 7075 | O | 3,6,9 | T62 |
| | T6 | 2,4,6 | T6 |

## 3. Results and Discussion

Precipitation hardenable alloys are usually formed in the T4 (naturally aged condition) or in the O (annealed) condition. They are rarely formed in the peak aged (T6 or T8) conditions where both the necking and fracture limits are low, (Ref 6, 7). However, in this work the 6061 and 7075 were formed in the T6 temper and the 2024 in the T8 temper for comparison purposes. All alloys were also formed in the O condition and 2024 was formed in the T3 temper.

In an earlier work, the influence of varying the solution treatment temperatures, quenching media and artificial aging conditions on the mechanical and physical properties of 7075-T6 alloy (Ref 8) and 6061-T6 and 7249-T76 alloys (Ref 9) were evaluated. Hardness, ultimate tensile strength and yield strength data increased proportional to each other, with a strong statistical correlation ($R^2 > 0.9$) in the 7075-T6 and 7249-T76 alloys (Ref 8, 9) and with a weak correlation in the 6061- T6 ($R^2 \sim 0.5$).

The hardness, ultimate strength and yield strength data had a weak inverse correlation with the electrical conductivity in all three alloys.

### *3.1 6061 alloy (initially T6)*

The ultimate strength values for the 6061-T6 alloy show an initial increase and then levels with no variation with the increase in the % cold work (strain applied) when tested in the T6 condition, Fig. 1(a). However, the yield strength values for this alloy, when formed in T6 and tested in T6, show a slight increase with the amount of cold work, Fig. 1(b). When formed in O condition and tested in T62, the ultimate and yield strengths initially decrease and then remain constant with the increase in cold work, Fig. 1(a and b). The ductility for the 6061 alloy, when formed in T6 and tested in T6, decreases significantly at 2% cold work and continues to decrease with more applied strain, Fig. 1(c). When formed in O and tested in the T62 condition, the percent elongation drops significantly after 4% cold work, Fig 1(c). The percent elongation remains at 5% or above in all cases. The conductivity decreases at 2% applied strain and remain constant when formed and tested in T6 condition and remain constant when formed in O and tested in T62, Fig. 1(d) which accords with the expected correlations, (Ref 9). The hardness values follow a similar trend to that of the ultimate and yield strengths, Fig. 1(e)

### *3.2 2024 alloy (initially T3)*

For the 2024 alloy formed in the O condition and tested in the T62 temper, the ultimate strength (Fig. 2(a)), the yield strength (Fig. 2(b)) decrease, the percent elongation increases, the conductivity decreases (Fig. 2(d)) and the hardness decreases, (Fig. 2(e)). The decrease of conductivity is not in accordance with the expected trend (Ref 8, 9). The percent elongation remained at 7-8% in all cases. For the alloy formed in the T3 temper and tested in the T81 temper the ultimate, yield strengths and hardness values increase, the conductivity and the percent elongation decrease with strain, Fig. (2a-e). The percent elongation remains at 4% even at 12% applied strain. For the alloy formed in the T8 temper and tested in the T8 temper, the yield and ultimate strengths slightly increase while the hardness values remain constant. The conductivity drops slightly and the percent elongation drops significantly to 2% after 4% applied strain.

### *3.3 7075 alloy (initially O)*

The ultimate strength and the yield strength values for the 7075 alloy show a slight increase with the increase in the amount of strain, Fig. 3(a and b). However, the yield strength of the alloy formed in the O condition and tested in T62 is significantly higher than that formed in T6 and tested in T6 temper. When formed in O and tested in T62, the ductility drops significantly after 6% of straining, Fig. 3(c). When formed in T6 condition and tested in T6 condition, there is a major decrease in ductility after 2% of straining, Fig. 3(c). For applied strains of 6% or less, the percent elongation was above 6% in all cases. The conductivity drops, Fig. 3(d), in accordance with the increase in ultimate and yield strength values. However, contrary to expectations, the hardness values dropped, Fig. 3(e), (Ref 8, 9).

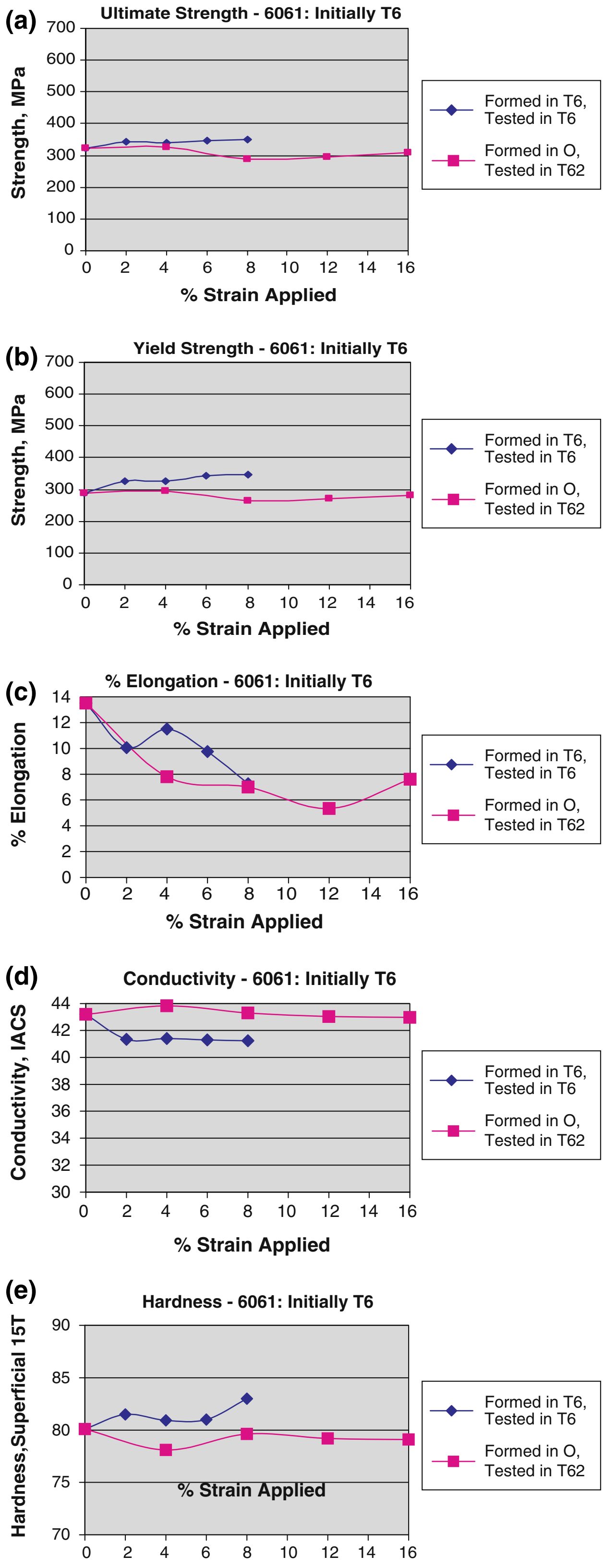

**Fig. 1** (a) Ultimate strength of the 6061 alloy initially in the T6 condition (b) Yield strength of the 6061 alloy initially in the T6 condition (c) % Elongation of the 6061 alloy initially in the T6 condition (d) Conductivity of the 6061 alloy initially in the T6 condition (e) Hardness of the 6061 alloy initially in the T6 condition

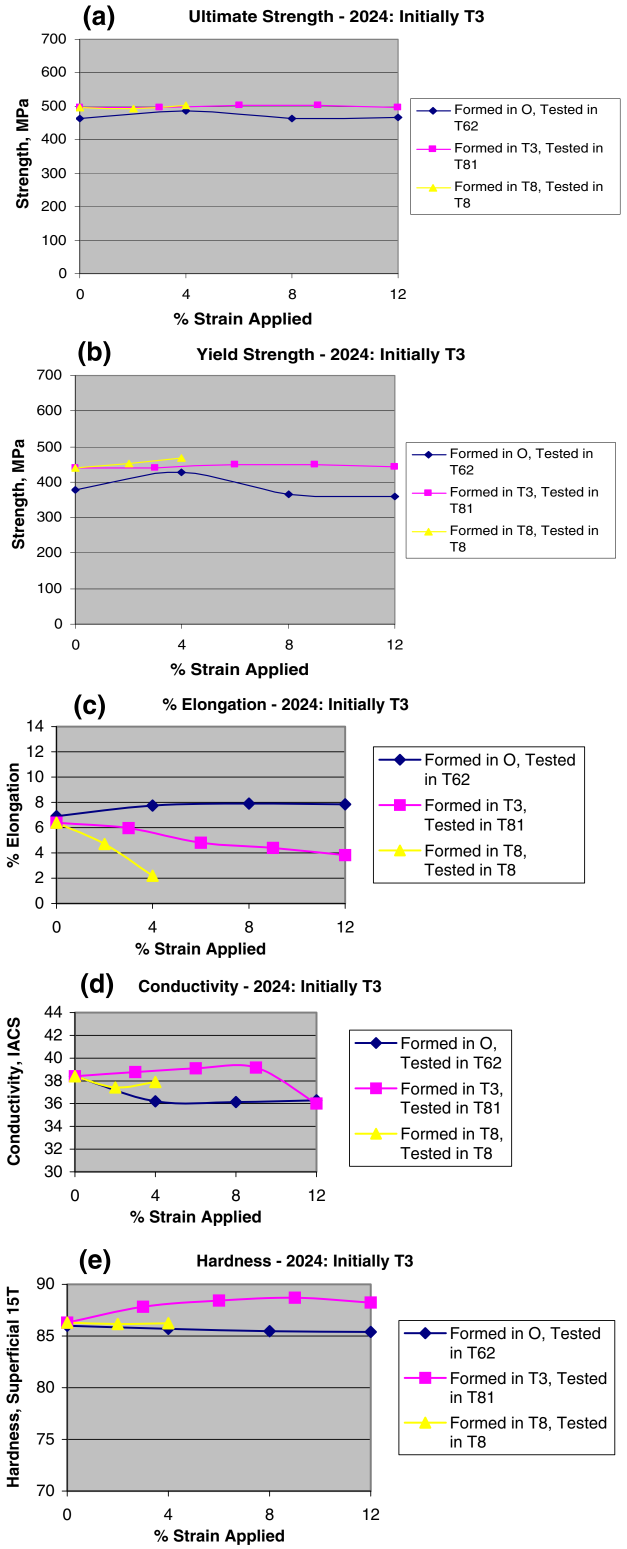

**Fig. 2** (a) Ultimate strength of the 2024 alloy initially in the T3 condition (b) Yield strength of the 2024 alloy initially in the T3 condition (c) % Elongation of the 2024 alloy initially in the T3 condition (d) Conductivity of the 2024 alloy initially in the T3 condition (e) Hardness of the 2024 alloy initially in the T3 condition

### *3.4 Microstructures*

Formability, including stretching of aluminum alloys require high elongation, wide forming range (spread between yield strength and tensile strength) and fine-grain structure within the amount of permissible deformation, (Ref 6, 7).

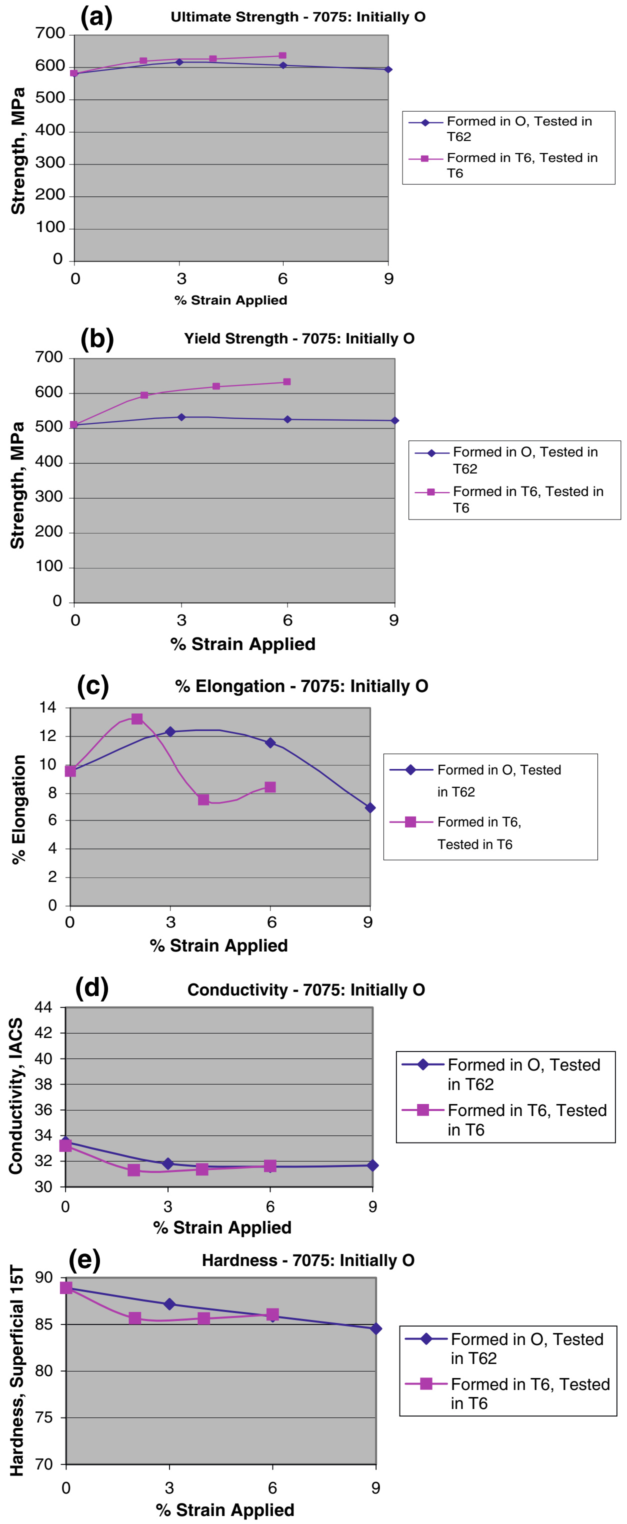

**Fig. 3** (a) Ultimate strength of the 7075 alloy (b) Yield strength of the 7075 alloy (c) % Elongation of the 7075 alloy (d) Conductivity of the 7075 alloy (e) Hardness of the 7075 alloy

Since the grains in both the longitudinal and transverse sections to the strain direction were non-equiaxed, the grain

**Table 5 6061 Grain sizes**

| | | | | Grain size, μm, longitudinal section | | Grain size, μm, transverse section | |
|---|---|---|---|---|---|---|---|
| **Initial** | **Form** | **Test** | **% Strain** | **Length** | **Width** | **Length** | **Width** |
| T6 | T6 | T6 | 2 | 29.8 | 13.2 | 29.4 | 13.7 |
| | | | 4 | 27.8 | 14.6 | 24.7 | 14.5 |
| | | | 6 | 34.5 | 15.2 | 29.0 | 13.9 |
| | | | 8 | 30.8 | 14.4 | 28.6 | 14.2 |
| T6 | O | T62 | 4 | 22.4 | 14.2 | 27.8 | 14.2 |
| | | | 8 | 30.8 | 15.5 | 37.7 | 15.2 |
| | | | 12 | 33.3 | 14.6 | 32.8 | 16.6 |
| | | | 16 | 33.3 | 16.4 | 29.9 | 16.5 |

**Table 6 2024 Grain sizes**

| | | | | Grain size, μm, longitudinal section | |
|---|---|---|---|---|---|
| **Initial** | **Form** | **Test** | **% Strain** | **Length** | **Width** |
| T3 | O | T62 | 0 | ... | ... |
| | | | 4 | 21.0 | 10.3 |
| | | | 8 | ... | ... |
| | | | 12 | ... | ... |
| T3 | T3 | T81 | 0 | 26.7 | 11.0 |
| | | | 3 | 36.4 | 14.5 |
| | | | 6 | 26.3 | 15.4 |
| | | | 9 | 32.3 | 15.6 |
| | | | 12 | 32.8 | 12.1 |
| T3 | T8 | T8 | 0 | 30.8 | 11.4 |
| | | | 2 | 24.7 | 10.4 |
| | | | 4 | 21.3 | 14.5 |

**Table 7 7075 Grain sizes**

| | | | | Grain size (μm) longitudinal section | |
|---|---|---|---|---|---|
| **Initial** | **Form** | **Test** | **% Strain** | **Length** | **Width** |
| O | O | T62 | 0 | 250 | 25.0 |
| | | | 3 | ... | ... |
| | | | 6 | 111 | 23.5 |
| | | | 9 | 167 | 27.4 |
| O | T6 | T6 | 0 | 143 | 29.9 |
| | | | 2 | 90.9 | 35.7 |
| | | | 4 | 100 | 37.8 |
| | | | 6 | 118 | 23.5 |

size reported here, in Table 5-7, indicates the longer dimension as length and the shorter dimension as width. Figures 4(a to c) show selected microstructures. The 7075 alloy has the most elongated grains.

### *3.5 Suggested Strain Limits*

**3.5.1 6061 (initially T6).** When forming in T6 and using in T6, caution should be exercised with strains of 2% or greater because ductility decreases significantly at 2% and continues to decrease with more applied strain. When forming in O and using in T62, caution should be exercised when straining 4% or greater because there is a major loss in ductility. Noticeable losses in strength occur at 8% strain.

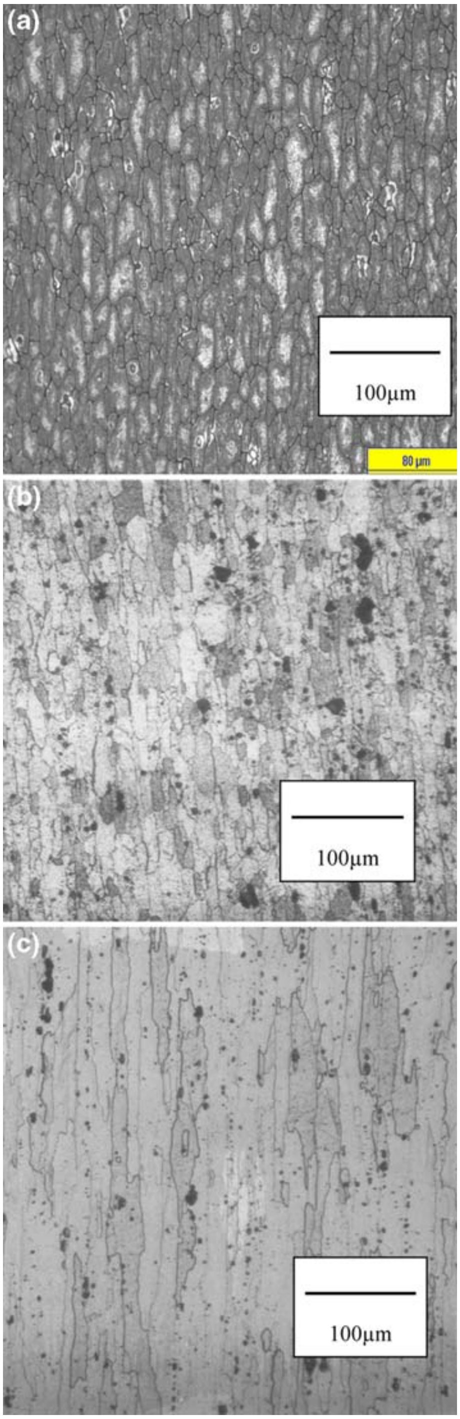

**Fig. 4** (a) 6061 Stretched 16% in O, Heat treated to T62: Longitudinal view (200 ×) (b) 2024 Stretched 4% in O, Heat treated to T62: Longitudinal view (200 ×) (c) 7075 Stretched 6% in O, Heat treated to T62: Longitudinal view (200 ×)

**3.5.2 2024 (initially T3).** When forming in O and using in T62, caution should be exercised when straining 8% or greater because there is approximately a 15% drop in yield strength. There is also a decrease in ultimate strength. When forming in T3 and using in T81, caution should be exercised when straining above 6% because there is a major loss of ductility. When forming in T8, caution should be exercised when straining above 2% because ductility drops sharply with any applied strain.

**3.5.3 7075 (initially O).** Caution should be exercised when straining above 9% or greater because ductility drops off significantly. When forming in T6 and using T6, caution should be exercised when straining 4% or greater because there is a loss in ductility. However, there is a general increase in strength up to this applied strain.

## 4. Conclusions

1. Strain limits are suggested for three aluminum alloys in various tempers.
2. Forming should be done in low-strength, high-ductility tempers.
3. Only small amounts of strain (2-3%) could be applied to hardened tempers (T6 and T8). Straining in these tempers is not an usual practice; however, these tempers were evaluated just for comparison purposes.

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