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**Al**
**0.90**
**Mg**
**0.80 Si**
**0.85 Cu**

## 1 General

Aluminum alloy 6013 is a relatively new heat-treatable alloy of medium strength which derives its heat-treat response from the precipitation of magnesium-silicon and magnesium-silicon-copper-aluminum phases.

It is primarily available as sheet, but other forms may become available as development progresses.

In the peak-aged T6 condition, it appears to be similar in yield strength, fracture toughness, and fatigue resistance to 2024-T3 sheet, but it has better corrosion resistance and lower density. These properties have made it a candidate for aircraft skins and other aerospace and automotive components.

In the solution-heat-treated (SHT) and naturally aged condition, T4, it has better stretch forming characteristics than 2024-O and can withstand greater deformation before fracturing. As the alloy hardens little during natural aging beyond the first two weeks, it can be supplied in the T4 condition and stored for months before forming. This property, and the good stretch formability, may in some cases preclude the need for in-plant SHT of O-temper materials and improve the economics of manufacturing.

It has been implied (Ref. 1), because of the superior corrosion resistance, that the alloy can be used in the bare condition instead of as clad 2024 sheet; however, this substitution must be examined on a case-by-case basis. Unclad alloy 6013 has a tendency to corrode intergranularly, with expected deterioration in fatigue resistance, ductility, and strength; and clad 6013 should be considered in cases where corrosion resistance is important (see Section 2.3.1).

### 1.1 Commercial Designation

6013 (UNS A96013).

### 1.2 Alternate Designation

### 1.3 Specifications

1.3.1 *[Table]* AMS specifications for 6013 alloy sheet.

### 1.4 Composition

1.4.1 *[Table]* AMS specified composition.

### 1.5 Heat Treatment

1.5.1 T Tempers. Solution heat treatment: soak 20 to 30 minutes at 1040 to 1060F, cold water quench, naturally age (room temperature) for 2 weeks to T4 temper. Artificially age T4 material at 375F for 4 hours to T6 temper (Ref. 1). Similar heat treatments can be used by the fabricator to produce T42 and T62 tempers from annealed sheet. Slower quench rates following solution heat treatment will reduce mechanical properties (Ref. 18). Glycol quenching will significantly lower tensile properties (see Figs. 3.2.1.5-3.2.1.8). Water mist quenching results in strengths below specified minima.

1.5.1.1 *[Table]* AMS specified heat treatments for sheet.

1.5.1.2 *[Figure]* Rockwell B hardness of 6013 sheet as a function of aging time at three different temperatures.

1.5.2 Annealing. Soak at 775F for 2 to 3 hours, cool at 50F per hour to 500F. The subsequent cooling rate is unimportant (Ref. 1).

1.5.3 Post-weld Heat Treatment. A solution heat treatment temperature of 1000F maximum is recommended instead of the above 1040 to 1060F in order to avoid melting of the filler metal (Ref. 1). As with most aluminum alloys during welding, chemical segregation within the weld metal or the heat-affected zone (HAZ) may lower the melting temperature.

### 1.6 Hardness (see also Figure 1.5.4)

1.6.1 *[Table]* Hardness of 6013 sheet of O, T4, T6, and T62 tempers.

### 1.7 Forms and Conditions Available

6013 is currently available as sheet, but probably only from the producer. Forgings, extrusions, plate, rod, and wire will probably become available on special order.

### 1.8 Melting and Casting Practices

This alloy is supplied in the wrought form and is not recommended for foundry applications.

### 1.9 Special Considerations

Although recommended as a substitute for 2024-T3 sheet, 6013-T6 is more susceptible to intergranular corrosion (IGC) below sheet gauges of approximately 0.063 in. Above this gauge, both alloys may suffer IGC due to slower achievable quench rates. This can have a greater effect on ductility and fatigue resistance than pitting or general corrosion (see Section 2.3.1).

An advantage of this alloy over 2024 is that the T4 temper is much more stable at room temperature than the W temper of 2024. The latter requires refrigeration to maintain formability for a few days, but 6013-T4 is still relatively formable after months at ambient temperatures.

Additionally, the T4 sheet has similar formability to 2024-O sheet; and after forming can be aged to peak strength at relatively low temperatures. The 2024-O sheet requires solution heat treatment, quenching, and aging after forming, with consequent distortion of the formed part (see Section 4.1).

Corrected October 1998

Sensitivity to grain growth has been reported (19) for naturally aged material strained from 2 to 13 percent prior to resolution heat treatment. This grain growth resulted in a decrease in yield strength. Backside cracking during fillet welding was increased for sheet which was strained prior to resolution heat treatment and cracking was also observed in full penetration welds using 4043 filler. Resolution heat treatment should not be used after forming of 6013.

## 2 Physical and Chemical Properties

### 2.1 Thermal Properties

2.1.1 Melting Range. The alloy commences to melt at 1075F (Ref. 2) or 1080F (Ref. 10); however, this temperature is dependent on the homogeneity of the structure, the exact composition, and the heating rate.

2.1.2 Phase Changes. The alloy is subject to precipitation, but the solid matrix is always face centered cubic.

2.1.2.1 Time temperature transformation diagrams.

2.1.3 Thermal Conductivity at Room Temperature.

2.1.3.1 *[Table]* Thermal conductivity at room temperature.

2.1.4 Thermal Expansion.

68F to 212F 13.0 x $10^{-6}$ in./in./deg. F (Ref. 2)
13.1 x $10^{-6}$ in./in./deg. F (Ref. 10)

2.1.5 Specific Heat.

0.23 BTU/lb. deg. F at 212F

2.1.6 Thermal Diffusivity.

### 2.2 Other Physical Properties

2.2.1 Density.

0.098 lbs/cu in. (2.715 g/cc) (Ref. 2)

2.2.2 Electrical Properties.

2.2.2.1 *[Table]* Electrical conductivity.

2.2.3 Magnetic Properties. Alloy is non-magnetic.

### 2.3 Chemical Environments

2.3.1 General Corrosion. The alloy has relatively good corrosion resistance compared with other age hardening aluminum alloys, but because of the significant copper content it suffers slightly more intergranular corrosion in the T6 temper than does 6061. Tests in which this slightly increased pitting corrosion has been reported (Ref. 2) include 5 percent salt spray at 95F, total immersion in shallow sea water, MASTMAASIS (ASTM G 85 Annex A3), pine wood contact at 195F, and seacoast and semi-industrial atmospheres. In these tests specimens of 0.120-in. sheet did not show increased sensitivity to these environments when heated to 180, and 250F for 50 hours prior to exposure (Ref. 3).

In contrast to the above mentioned results in marine environments, seacoast exposure of T6 sheet at Daytona Beach produced significant pitting corrosion coupled with intergranular corrosion (IGC) similar to that developed in SWAACT (sea water acetic acidified corrosion test) or TOA (type of attack) tests (Refs. 9, 11). In the Daytona Beach tests large losses in elongation were observed for the thinner sheet gages, and a corresponding large loss in strength occurred for the thinnest gage (0.032 in.) (Figure 2.3.1.1). This type of thickness effect would be expected as a result of the pitting and IGA and may explain why no such losses were noted for the thicker sheet reported in Ref. 2. IGC has been reported in ASTM G 85 salt fog tests (Ref. 1). For 0.032-in. sheet complete perforation due to IGC occurred during a 7-day exposure in SWAACT tests (Ref. 11).

The Daytona Beach tests included 6061-T6 and 2024-T3. A comparison of the results for 0.063-in. sheet is shown in Figure 2.3.1.2. It will be noted that both 6013 and 6061 behave similarly while 2024 shows losses in both strength and elongation. Bare and clad 6013-T6 and 2024-T3 are compared in Figure 2.3.1.3. Cladding effectively protects both alloys for the 12 month exposures.

2.3.1.1 *[Figure]* Effect of seacoast exposure on retained tensile properties of 6013-T6 sheet of several thicknesses.

2.3.1.2 *[Figure]* Effect of seacoast exposure on retained tensile properties of 6013-T6, 6061-T6, and 2024-T3 sheet.

2.3.1.3 *[Figure]* Effect of seacoast exposure on retained tensile properties of bare and clad 6013-T6 and 2024-T6 sheet.

2.3.2 Stress Corrosion.

The SCC resistance of 6013 has been reported (Ref. 1) to be equal to that of 6061 which is essentially immune. Tests on 144 specimens of plate and extrusions resulted in no failure when stressed to 75 percent of $F_{ty}$ and exposed for one year to alternate immersion in 3.5 percent NaCl solution and to seacoast environment at Point Judith, RI, for two years (Ref. 2).

### 2.4 Nuclear Properties

## 3 Mechanical Properties

### 3.1 Specified Mechanical Properties

3.1.1 *[Table]* Aluminum Association specified minimum tensile properties.

3.1.2 *[Table]* AMS specified tensile properties for sheet.

3.1.3 *[Table]* Design mechanical properties for 6013-T6 sheet.

## 3.2 Mechanical Properties at Room Temperature

3.2.1 Tension.

3.2.1.1 *[Figure]* Tensile stress-strain curves for 6013-T6 sheet.

3.2.1.2 *[Figure]* True stress, true strain tensile curve for 6013-T4 sheet.

3.2.1.3 *[Figure]* Load-displacement curve for a longitudinal tensile test of 0.08-in. thick 6013-T4 sheet.

3.2.1.4 *[Figure]* Load-displacement curve for a long-transverse tensile test of 0.08-in. thick 6013-T4 sheet.

3.2.1.5 *[Figure]* Load-displacement curve for a longitudinal tensile test of 0.08-in. thick 6013-T6 sheet.

3.2.1.6 *[Figure]* Load-displacement curve for a long-transverse tensile test of 0.08-in. thick 6013-T6 sheet.

3.2.1.7 *[Figure]* Load-displacement curve for a longitudinal tensile test of 36% PAG (glycol) quenched 0.08-in. thick 6013-T6 sheet.

3.2.1.8 *[Figure]* Load-displacement curve for a long-transverse tensile test of 36% PAG (glycol) quenched 0.08-in. thick 6013-T6 sheet.

3.2.1.9 Directionality of tensile properties.

3.2.1.9.1 *[Figure]* Tensile properties of 0.063-in. thick sheet as a function of the angle between the rolling direction and the tensile axis.

3.2.2 Compression.

3.2.2.1 *[Figure]* Compression stress-strain curves for 6013-T6 sheet at room temperature (Ref. 2).

3.2.3 Impact.

3.2.4 Bending, see Table 4.1.1

3.2.5 Torsion and Shear, see Table 3.1.3

3.2.6 Bearing, see Table 3.1.3

3.2.7 Stress Concentration.

3.2.7.1 Fracture toughness. As this alloy has been made largely in thin sections, little plane-strain fracture toughness data could be found (Table 3.2.7.1.1).

Most toughness measurements have been plane-stress fracture toughness, $K_c$, which is usually measured using the specimen described in ASTM E 561 and analysis described in ASTM B 646 (see Figure 3.2.7.1.3 and Table 3.2.7.1.2). The $K_{apparent}$ in Fig. 3.2.7.1.3 refers to values measured using specimens described in ASTM E 561 but using the original crack length in calculating the K values. This presumably could give conservative results. However, it is likely that the $K_{apparent}$ values are relatively insensitive to the material's fracture toughness due to the small specimen size. Thus a valid $K_c$ value for 6013-T6 would require a specimen width of over 15.75 in. None of the data reported here were obtained from specimens having a width exceeding 9.5 in.

3.2.7.1.1 *[Table]* Comparison of the plane-strain fracture toughness of 6013-T6 plate with 6061-T651 and 2024-T351.

3.2.7.1.2 *[Table]* Fracture toughness of 6013-T6 sheet in comparison with 2024-T3 and 6061-T6.

3.2.7.1.3 *[Figure]* Fracture toughness of 6013-T6 sheet of various gauges.

3.2.7.1.4 *[Table]* Kahn tear test results for 6013-T6 sheet.

3.2.7.1.5 *[Figure]* Range of crack-growth resistance curves (R-curves) for 6013-T6 sheet of thicknesses 0.063-in., 0.080-in., and 0.100-in.

## 3.3 Mechanical Properties at Various Temperatures

3.3.1 Tension.

3.3.2 Compression.

3.3.3 Impact.

3.3.4 Bending.

3.3.5 Torsion and Shear.

3.3.6 Bearing.

3.3.7 Stress Concentration.

3.3.7.1 Fracture toughness, see Figure 3.2.7.1.3.

3.3.8 Combined Properties.

## 3.4 Creep and Creep Rupture Properties

## 3.5 Fatigue Properties

The resistance to fatigue in the presence of a notch is superior to that of 6061-T6; for smooth specimens the fatigue strengths are about equal. The smooth specimen fatigue performance is about equal to 2024-T3 for lives greater than $10^5$ cycles, but is inferior for shorter lives (Ref. 2). Fatigue crack-growth rates under constant amplitude in both L-T and T-L orientations are similar to 6061-T6 (Ref. 2).

3.5.1 Conventional Fatigue Properties.

3.5.1.1 *[Figure]* Comparison of smooth and notched specimens in S-N fatigue for 6013-T6 sheet of various gauges.

3.5.1.2 *[Figure]* S-N fatigue curves for smooth specimens of 6013-T6 sheet of thicknesses 0.063-in., 0.080-in., and 0.100-in.

3.5.2 Fatigue Crack Propagation.

3.5.2.1 *[Figure]* Fatigue crack-growth rates of 6013-T6 sheet 0.063-in. thick.

3.5.2.2 *[Figure]* Fatigue crack-growth rates of 6013-T6 sheet from 0.063 to 0.249-in. thick in L-T orientation.

3.5.2.3 *[Figure]* Fatigue crack-growth rates of 6013-T6 sheet from 0.063 to 0.249-in. thick in T-L orientation.

3.5.2.4 *[Figure]* Fatigue crack-growth rates for 6013-T6 sheet tested at a stress ratio of 0.4.

3.5.2.5 *[Figure]* Fatigue crack-growth rates for 6013-T6 sheet tested at a stress ratio of 0.8.

3.5.2.6 *[Figure]* Fatigue crack-growth rates for 6013-T6 sheet tested at a stress ratio of 0.1.

### 3.6 Elastic Properties

3.6.1 Poisson's Ratio, 0.33 (Ref. 4).

3.6.2 Tensile Elastic Modulus.
$10 \times 10^6$ psi (Ref. 10).
$9.9 \times 10^6$ psi (Refs. 2, 4).

3.6.3 Compression Modulus.
$10.1 \times 10^6$ psi (Refs. 2, 4).

3.6.3.1 *[Figure]* Compressive tangent modulus for 6013-T6 sheet (Ref. 2).

## 4 Fabrication

### 4.1 Forming

The alloy is formable as extrusions and as sheet (see remarks in Section 1.9).

4.1.1 *[Table]* Comparison of the formability of 6013, 2024, and 6061 in various tempers.

4.1.2 *[Table]* Bend radii for 6013 sheet in various tempers and thicknesses.

### 4.2 Machining and Grinding

4.2.1 The alloy in T6 condition is reported to have good chemical milling properties (Ref. 3).

### 4.3 Joining

4.3.1 This alloy is weldable by the GTA, MGA and resistance methods (Refs. 12 and 3). Filler wires of 4043 and 4063 are recommended. Fusion line cracking may be encountered when using Mg bearing fillers (e.g. 5000 series). Welability has been rated as A (Ref. 4) essentially equivalent to 6061. However recent information (Ref. 19) has indicated that in the T4 condition, weld cracking in fillet welds and in full penetration welds using 4043 filler is more pronounced in 6013 than in 6061. This relative increase in cracking may be associated with sensitivity to grain growth (See 1.9). For sound welds the strengths are 4 to 6 percent higher than obtained for 6061.

4.3.1.1 *[Table]* Tensile properties of GTA sheet welds.

### 4.4 Surface Treatment

Anodizing response is claimed to be similar to 6061 and superior to 7075 (Ref 2).

Excellent chemical milling quality has been reported (Ref. 3).

Table 1.3.1 AMS specifications for 6013 sheet (Refs. 14, 15)

| Alloy: 6013 | | |
|---|---|---|
| Form | Sheet | |
| Temper | T4 | T6 |
| AMS | 4347A | 4216 |

Table 1.4.1 AMS specified composition (Refs. 14, 15)

| Alloy: 6013 | | |
|---|---|---|
| Form | Sheet | |
| | Composition, percent | |
| Element | Min | Max |
| Mg | 0.8 | 1.0 |
| Cu | 0.6 | 1.1 |
| Si | 0.6 | 1.0 |
| Mn | 0.20 | 0.8 |
| Fe | - | 0.50 |
| Zn | - | 0.25 |
| Cr | - | 0.10 |
| Ti | - | 0.10 |
| Other, each | - | 0.05 |
| Other, total | | 0.15 |

Table 1.5.1.1 AMS specified heat treatments for sheet (Ref. 16)

| Alloy: 6013 | |
|---|---|
| **Form** | **Sheet** |
| Solution Treat | 1055F, 1/2 hr |
| Quench | < 1/8 in. A.C. |
| | > 1/8 in. W.Q. |
| Natural Age T4 | R.T. 336 hr minimum |
| Artifical Age T6 | 375F 4 to 5 hrs |

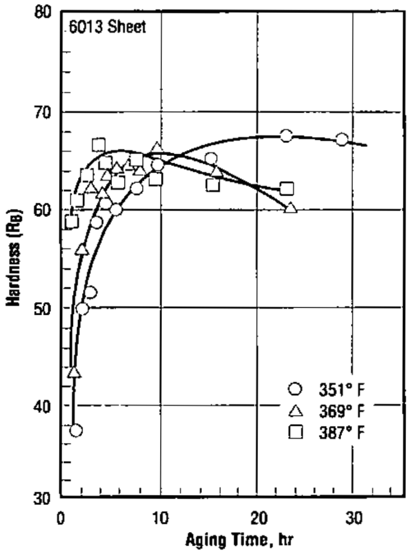

Fig. 1.5.1.2 Rockwell B hardness of 6013 sheet as a function of aging time at three different temperatures (Ref. 12)

Table 2.1.3.1 Thermal conductivity at room temperature

| Alloy: 6013 | | |
|---|---|---|
| **Form** | **Sheet** | |
| **Temper** | **Thermal Conductivity (Btu/hr ft$^2$ deg F/in.)** | **Reference** |
| T4 | 1032 | 2 |
| T6 | 1140 | 2 |
| O | 1250 | 10 |
| T4 | 1070 | 10 |
| T6 | 1160 | 10 |

Table 1.6.1 Hardness of 6013 sheet of O, T4, T6 and T62 tempers (Ref. 13)

| Alloy: 6013 | | | |
|---|---|---|---|
| **Form** | **Sheet** | | |
| **Thicknes** | **0.063 in.** | | |
| **Temper** | **Hardness (Rockwell** | **Standard Deviatio** | **No. of T** |
| T62 | 85.16 | 0.29 | 36 |
| T6 | 82.38 | 0.37 | 45 |
| T4 | 79.15 | 0.69 | 30 |
| O | 47.77 | 2.01 | 42 |

Table. 2.2.2.1 Electrical conductivity

| Alloy: 6013 | | | |
|---|---|---|---|
| **Form** | **Sheet** | | |
| **Temper** | **IACS, (percent)** | **m(ohms/mm$^2$)** | **Reference** |
| T4 | 38.3 | 22.2 | 2 |
| T6 | 42.5 | 24.6 | 2 |
| O | 47 | - | 10 |
| T4 | 40 | - | 10 |
| T6 | 43 | - | 10 |

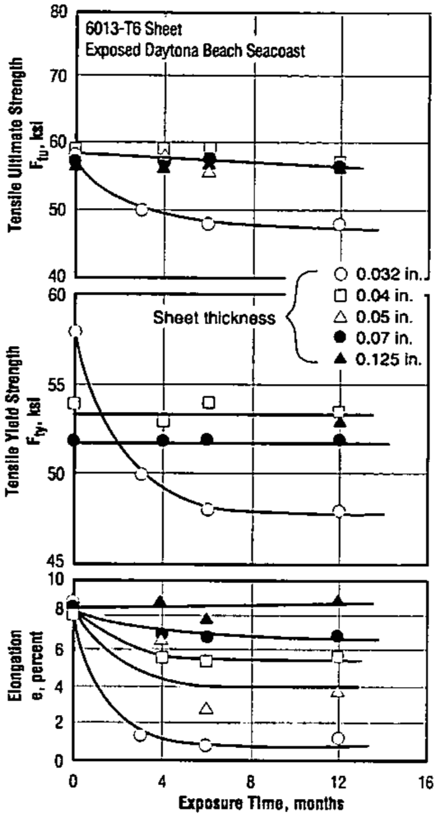

Fig. 2.3.1.1 Effect of seacoast exposure on retained tensile properties of 6013-T6 sheet of several thicknesses (Ref. 9)

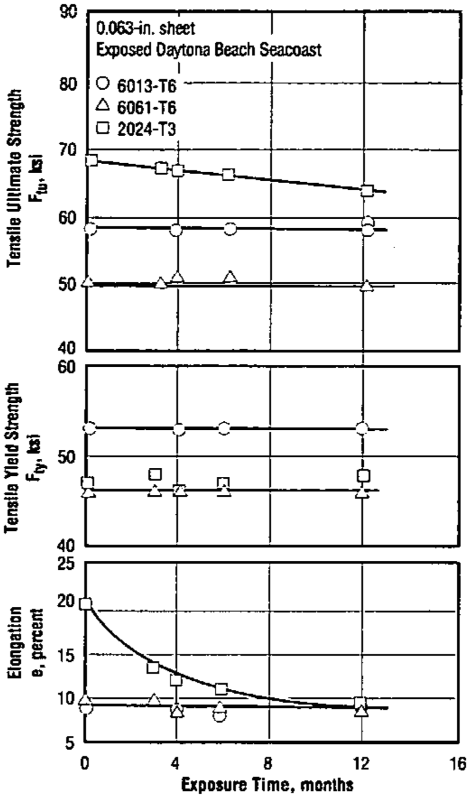

Fig. 2.3.1.2 Effect of seacoast exposure on retained tensile properties of 6013-T6, 6061-T6 and 2024-T3 sheet (Ref. 9)

Table 4.3.1.1 Tensile properties of GTA sheet welds (Ref. 18)

| Alloy: 6013 | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Form** | **0.10-to 0.13-in. Sheet** | | | | | | |
| **Weld/H.T.** | **T4 + Weld** | **T6 + Weld** | **T4 + Weld + T6 Age** | **T6 + Weld + T6 Age** | **T4 + Weld + ST WQ + T6 Age** | **T4 Weld + ST 36% Glycol Q + T6 Age** | **T4 + Weld + ST Mist Q + T6 Age** |
| As welded (a) | | | | | | | |
| $F_{tu}$ (ksi) | 37 | 36 | 37 | 38 | 55 | 54 | 50 |
| $F_{ty}$ (ksi) | 26 | 26 | 31 | 35 | 48 | 47 | 41 |
| e (percent) | 4.8 | 3.2 | 2.5 | 2.6 | 10 | 10.7 | 10.3 |
| Failure Location (b) | 3HAZ | 3HAZ | 3HAZ | 3HAZ | 3HAZ | 3HAZ | 3HAZ |
| Weld Machined Flush | | | | | | | |
| $F_{tu}$ (ksi) | 33 | 36 | 37 | 36 | 41 | 47 | 43 |
| $F_{ty}$ (ksi) | 23 | 24 | 29 | 30 | 38 | 42 | 38 |
| e (percent) | 3.5 | 4.7 | 3 | 2.9 | 5.7 | 3.2 | 2.8 |
| Failure Location (b) | 3W | 1W/2HAZ | 1W/2HAZ | 1W/2HAZ | 3W | 3W | 3Q |

(a) GTA square butt, 2-pass welds with 4043 filler using 6061 parameters

(b) Number of specimens failed in weld/number failed in HAZ. There was no discernable difference between strengths of weld and HAZ failures but elongations were slightly lower for weld failures

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