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# Composition Matters

## Understanding the composition of aluminum alloys can boost milling productivity.

*Part 1 of 2*

Ingersoll Cutting Tools

It's a metal that people come into contact with every day—from cans to cars to you name it. The metal is aluminum, and it's classified into two major groups: wrought and cast.

The first part of this two-part article covers the designation system for wrought aluminum and aluminum alloys and their temper (a process that improves physical and mechanical properties), the relationship between hardness of aluminum alloys and their strength, milling data and a method of calculating the machining power required to maximize productivity from a given machine tool.

### Alloy Designation

The designation system for wrought aluminum and aluminum alloys was developed by the American National Standards Institute (ANSI) and adopted by The Aluminum Association Inc. in the United States.

A four-digit numerical designation system is used to identify wrought aluminum and aluminum alloys, which are divided into eight groups. The first digit indicates the following groups.

Equal to or greater than 99.0 percent aluminum is designated 1xxx. Aluminum alloys are grouped by major alloying element or elements. An aluminum alloy with copper as the major alloying element is designated 2xxx, manganese is 3xxx, silicon is 4xxx, magnesium is 5xxx, magnesium and silicon is 6xxx and zinc is 7xxx. Other elements are designated 8xxx.

In the 1xxx group, the series 10xx designates unalloyed aluminum grades that have natural impurity limits. Designations having a second digit other than zero (integers 1 through 9) indicate special control of one or more individual impurities, such as 11xx, 12xx, 13xx and 14xx. The last two of the four digits in the designation indicate the minimum aluminum percentage to the nearest 0.01 percent. For example, the 1098 grade contains 99.98 percent aluminum. Currently, there are nearly 40 grades containing 99.00 to 99.99 percent aluminum, from 1100 (99.00 percent) to 1199 (99.99 percent). These are used primarily in the electrical and chemical fields for products such as conductors, capacitors, heat exchangers, packaging foil and chemical equipment.

Aluminum is characterized by excellent corrosion resistance and high electrical and thermal conductivities.

## Does roughing operation qualify as high-speed machining?

The following case study is based on information provided by Perry Keifer, machine shop manager for Rovema Packaging USA, Lawrenceville, Ga.

Workpiece material: Blocks of 6061-T6 aluminum

End product: Disc brake calipers for racecars

Cutting tool: Integral-shank endmill, high-positive axial geometry, indexable carbide inserts with grade DC 20 diamond coating

Tool diameter (D): 2.0"

Number of inserts (Z): 5

Machine tool: Okuma & Howa vertical machining center

Machine's nominal power: 30 hp

Type of drive: Direct drive

Spindle taper: CAT 40

Machining parameters for roughing operation:

- DOC: 0.375"
- WOC (W): 2.0"
- Spindle speed (n): 10,000 rpm
- Feed rate (F): 300 ipm

Based on this data, the author performed the following routine calculations to determine whether or not this roughing operation qualifies as high-speed machining.

Cutting speed:

$V_C = (\pi \times D \times n) \div 12 = 5{,}236$ sfm

Metal-removal rate (mrr):

$Q = DOC \times WOC \times F = 0.375 \times 2 \times 300 = 225$ in.$^3$/min.

Feed per tooth:

$f_z = F \div (Z \times n) = 300 \div (5 \times 10{,}000) = 0.006"$

The values of the cutting speed (5,236 sfm) and mrr (225 in.$^3$/min.) indicate high-speed machining in this application at a high-productivity level. However, the maximum productivity from a given machine is achieved when the required machining power—in a long run—is about the same as the machine tool's nominal power.

Required machining power can be calculated through the tangential cutting force and the cutting speed. Calculating the tangential cutting force through the ultimate tensile strength of the workpiece material and the cross-sectional area of uncut chip is more accurate than the estimations provided by other methods.

**Machining power and torque requirements.**

| | Tempers of 6061 aluminum alloy | | |
|---|---|---|---|
| | 0 | T4 | T6 |
| Brinell hardness at 500 kg load | 30 | 65 | 95 |
| Ultimate tensile strength, psi | 18,000 | 35,000 | 45,000 |
| Tangential cutting force, lbs. | 91 | 177 | 228 |
| Required machining power, hp | 15.2 | 29.6 | 38.0 |
| Required torque, ft.-lbs. | 7.6 | 14.8 | 19.0 |

The author developed a new method for performing such calculations, as well as the formulas, which are described in his book, "Engineering Formulas for Metalcutting."

The most common method of calculating machining power is based on the mrr and a specific power, which is also known as p factor or power constant. Published power constant data may vary significantly and is usually overestimated, sometimes by more than 40 percent. Specific power in milling for all aluminum alloys recommended by "Machining Data Handbook" is 0.32 hp/in.$^3$/min. It means that the required machining power in this case should be: 225 in.$^3$/min. × 0.32 hp/in.$^3$/min = 72 hp.

All necessary step-by-step calculations of required machining power are omitted. Calculations were performed for the 0, T4 and T6 tempers of 6061 aluminum alloys for comparison. The cutting force, machining power and torque are increasing with the increase of the work material's ultimate tensile strength, depending on the type of temper (see table).

The required machining power of 38 hp for rough milling of 6061-T6 aluminum alloy at the selected cutting conditions exceeds the Okuma & Howa's nominal power of 30 hp by 27 percent. Rovema's Keifer confirmed that the machine tool's power meter has shown that power consumption was higher than 100 percent, adding that this VMC can run at up to a 150 percent load for 30 minutes without any problems.

—*E. Isakov*

Mechanical properties, such as hardness and strength, are low. Therefore, grades with 99 percent or more aluminum are not suitable to be machined as workpiece materials, but aluminum alloys are. After steel, aluminum alloys are the most machined material.

### Temper Designation

The temper designation system is based on the sequences of mechanical or thermal treatments, or both, to produce the various tempers, which include the basic tempers and subdivisions of basic tempers.

Basic temper is designated by a capital letter.

- F (as fabricated) is applied to products when the mechanical property limits are not specified.
- O (annealed) indicates products that have been annealed to obtain the lowest-strength temper.
- H (strain hardened, applied to wrought products only) indicates products that have been strengthened by strain hardening, with or without supplemental thermal treatment to reduce some strength.
- T (solution heat-treated) applies to products that have been strengthened by heat treatment, with or without subsequent strain hardening.

Subdivisions of basic tempers are applied to strain-hardened (H) and solution heat-treated (T) products.

Strain-hardened designations consist of the letter H followed by one or more digits. The first digit (1, 2 or 3) indicates the specific sequence of basic operations.

- H1 (strain hardened only) applies to products that are strain hardened to obtain the desired strength without supplemental thermal treatment.
- H2 (strain hardened and partially annealed) pertains to products that are strain hardened more than the desired strength and then reduced in strength to the desired level by partial annealing. Aluminum alloys' strength and hardness are imparted through strain hardening, whereas partial annealing reduces hardness. Because a metal's strength is directly proportional to the hardness, a decrease in hardness results in lower strength.
- H3 (strain hardened and stabilized) applies to products that are strain hardened and whose mechanical properties are stabilized by a low-temperature thermal treatment.

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## Additional Temper Designations

A number from 1 through 9 following the designations H1, H2 and H3 indicates a degree of strain hardening—a two-digit H temper. The number 8 indicates tempers with ultimate tensile strength equivalent to that achieved by cold reduction at a temperature not exceeding 120° F following full annealing. For example, actual tensile strength of 5052-H38 aluminum alloy is 42,000 psi. The number 9 designates tempers whose minimum ultimate tensile strength exceeds that of the 8 temper by 2,000 psi or more.

Aluminum alloys having an ultimate tensile strength approximately midway between that of the zero (annealed) temper (actual tensile strength of 5052-O aluminum alloy is 28,000 psi) and the 8 temper are designated by the number 4 [actual tensile strength of 5052-H34 is 38,000 psi; calculated value is (28,000 + 42,000) ÷ 2 = 35,000 psi]. Midway between the zero and the 4 tempers are designated by the number 2 [actual tensile strength of 5052-H32 is 33,000 psi; calculated value is (28,000 + 38,000) ÷ 2 = 33,000 psi]. Midway between the 4 and 8 tempers are designated by the number 6 [actual tensile strength of 5052-H36 is 40,000 psi; calculated value is (38,000 + 42,000) ÷ 2 = 40,000 psi]. For two-digit H tempers whose second digits are odd, the standard limits for strength are the arithmetic mean of the standard limits for the adjacent two-digit H tempers whose second digits are even. For example, the estimated tensile strength of 5052-H35 aluminum alloy is based on tensile strengths of 5052-H34 (38,000 psi) and 5052-H36 (40,000 psi), so the estimated tensile strength of 5052-H35 aluminum alloy is (38,000 + 40,000) ÷ 2 = 39,000 psi.

To identify a variation of a two-digit H temper, a third digit (from 1 to 9) may be assigned, and presently digits 1, 2 and 3 are in use. A three-digit H temper is used when the mechanical properties are different from but close to those for the two-digit H temper designation to which it is added.

- ■ With Hxx1, the third digit applies to products that are strain hardened less than the amount required for controlled Hxx tempers. As previously mentioned, the first "x" is a digit from 1 to 3, and the second "x" is a digit from 1 to 9. For example, ultimate tensile strength of aluminum alloy 5083-H321 is 46 ksi and that of aluminum alloy 5083-H32 is 47 ksi.
- ■ H112 pertains to products that may acquire some strain hardening during working at elevated temperature and for which there are mechanical property limits. The following aluminum alloys are of this type of temper: 5086-H112, 5154-H112, 5254-H112, 5454-H112 and 5456-H112 (besides various two-digit H tempers).
- ■ H323 and H343 apply to products that are fabricated to resist stress corrosion cracking, such as 5083-H323 and 5083-H343.

Solution heat-treated designations consist of the letter T followed by a number from 1 through 10 to indicate a spe-

cific sequence of basic treatments.

- T1 applies to products that are cooled from an elevated-temperature shaping process and naturally aged to a substantially stable condition.
- T2 applies to products that are cooled from an elevated-temperature shaping process, cold worked and naturally aged to a substantially stable condition.
- T3 indicates solution heat-treated, cold worked and naturally aged to a substantially stable condition.
- T4 indicates solution heat-treated and naturally aged to a substantially stable condition.
- T5 applies to products that are cooled from an elevated-temperature shaping process and artificially aged.

**Because tempers affect an alloy's strength and hardness, end users must have this information to achieve maximum productivity when milling aluminum alloys.**

- T6 indicates solution heat-treated and artificially aged. Artificially aged, or artificial age hardening, is a heat-treated process where material is hardening more rapidly at temperatures higher than room temperature.
- T7 indicates solution heat-treated and overaged or stabilized.
- T8 indicates solution heat-treated, cold worked and artificially aged.
- T9 indicates solution heat-treated, artificially aged and cold worked.
- T10 applies to products that are cooled from an elevated-temperature shaping process, cold worked and artificially aged.

### Additional T Temper Designations

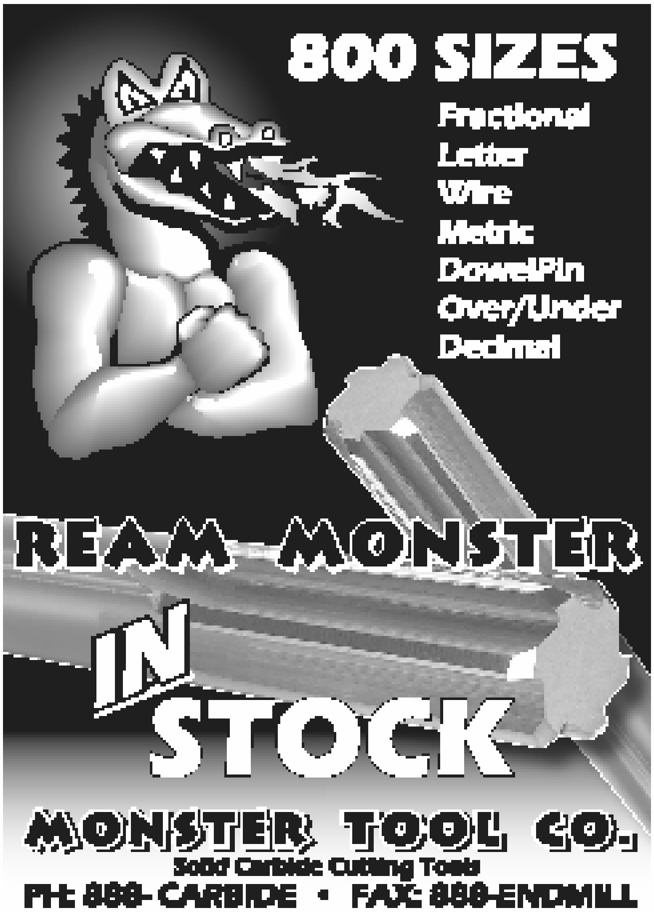
When it is desirable to identify a variation of one of the 10 major T tempers described previously, additional digits, the first of which cannot be zero, may be added to the designation.

- Tx51 applies to products that are stress relieved by stretching, such as aluminum alloys 2024-T351, 6061-T451 and 7075-T651.
- Tx511 refers to products that may receive minor straightening after stretching to comply with standard tolerances, such as aluminum alloys 2024-T3511, 6061-T4511 and 7075-T6511.
- Tx52 applies to products that are stress relieved by compressing after solution heat treatment, such as aluminum alloys 6061-T652 and 6151-T652.
- Tx510 applies to products that receive no further straightening after stretching, such as aluminum alloys 2024-T3510, 2024-T8510, 6061-T4510 and 7075-T6510.

### Alloying Elements

In the 2xxx through 8xxx aluminum alloy groups, the second digit in the designation indicates alloy modification. If the second digit is zero, it indicates the original alloy. Numbers 1 through 9, assigned consecutively, indicate original alloy modifications. The last two of the four digits have no special significance. Due to space limitations, only three of the seven aluminum alloy groups are described.

Copper is the principal alloying element, often with magnesium as a secondary addition, in the 2xxx series. The amount of copper varies from 0.7 to 6.8 percent. The majority of grades contain magnesium in amounts from 0.4 to 0.8 percent or 1.0 to 1.9 percent. Currently, there are 35 standard grades, including 24 original alloys (2001 to 2091) and 11 modified alloys: two grades of the first modification (2117 and 2124), four grades of the second modification (2214, 2218, 2219 and 2224), two grades of the third modification (2319 and 2324) and by one grade in each of the three subsequent modifications (2419, 2519 and 2618). Alloys in the 2xxx series are commonly used to make truck and aircraft wheels, aircraft fuselage and wing skins and structural parts requiring high strength at temperatures up to 300° F (2014, 2024 and 2048); aircraft and diesel engine pistons, aircraft engine cylinder heads and jet engine impellers and compressor rings (2218); and pistons and rotating aircraft engine parts for operation at elevated temperatures (2618).



One popular grade is 2024. It is available in several tempers, which are characterized by various mechanical properties (Table 1). As the table shows, solution heat-treated tempers (T3, T4 and T361) produce significantly higher strength and hardness compared with temper O (annealed condition).

In the 5xxx series alloy group, magnesium is the principle alloying element. The majority of these grades have 1.0 to 5.6 percent magnesium. Currently, there are 47 standard grades, including 18 original alloys (5005 to 5086) and 29 modified alloys (5150 to 5854). Finished products containing these original and modified alloys include automotive and aircraft parts (5083, 5086, 5252), cryogenic tanks (5083, 5086) and household appliances (5005, 5052). Numerous grades effectively resist corrosion in marine environments (5052, 5083, 5086, 5154, 5456).

One of the popular grades for marine and transport applications is 5052. This grade is available in several tempers, which are characterized by various mechanical properties (Table 2). As can be seen from the table, strain-hardened and stabilized temper H3 at various degrees of strain hardening (2, 4, 6 and 8) increase ultimate strength by 18 to 50 percent and hardness by 28 to 64 percent.

Alloys in the 6xxx series group have 0.3 to 1.5 percent magnesium and 0.2 to 1.8 percent silicon. Currently, there are 45 standard grades, including 24 original alloys (6002 to 6082) and 21 modified ones (6101 to 6951). These standard and modified alloys offer good machinability and corrosion resistance and are used to make transportation equipment, bridge railings, bicycle frames, architectural parts and welded structures.

One of the popular grades used in the automotive industry is 6061—a free-machining grade. It is available in several tempers, which are characterized by various mechanical

**Table 1: Typical mechanical properties of alloy 2024.**

| Temper | Tensile strength, psi | Yield strength, psi | Shear strength, psi | Brinell hardness at 500 kg load |
|---|---:|---:|---:|---:|
| 0 | 27,000 | 11,000 | 18,000 | 47 |
| T3 | 70,000 | 50,000 | 41,000 | 120 |
| T4 | 68,000 | 47,000 | 41,000 | 120 |
| T361 | 72,000 | 57,000 | 42,000 | 130 |

**Table 2: Typical mechanical properties of alloy 5052.**

| Temper | Tensile strength, psi | Yield strength, psi | Shear strength, psi | Brinell hardness at 500 kg load |
|---|---:|---:|---:|---:|
| 0 | 28,000 | 13,000 | 18,000 | 47 |
| H32 | 33,000 | 28,000 | 20,000 | 60 |
| H34 | 38,000 | 31,000 | 21,000 | 68 |
| H36 | 40,000 | 35,000 | 23,000 | 73 |
| H38 | 42,000 | 37,000 | 24,000 | 77 |

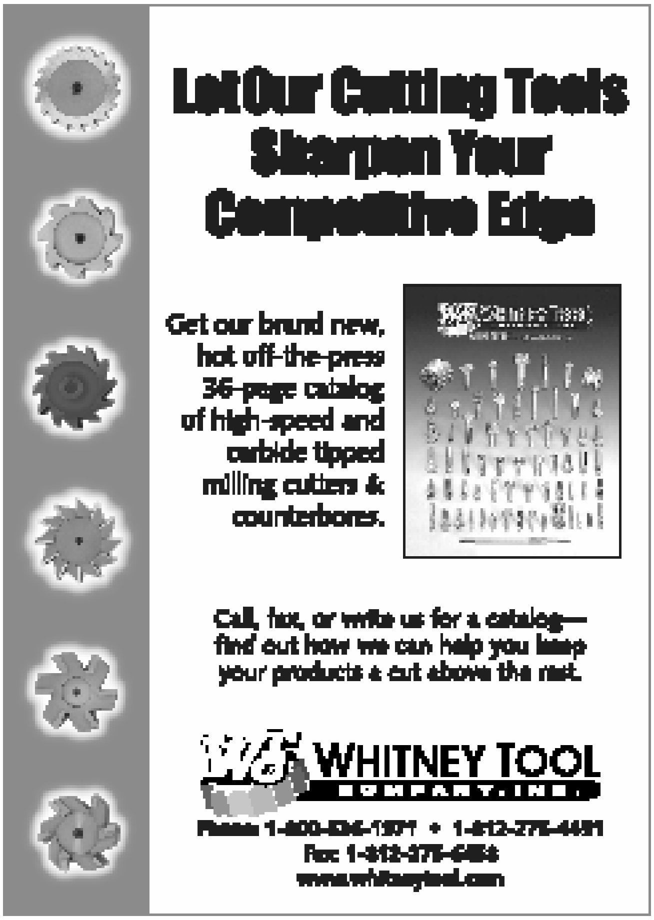


**Table 3: Typical mechanical properties of alloy 6061.**

| Temper | Tensile strength, psi | Yield strength, psi | Shear strength, psi | Brinell hardness at 500 kg load |
|---|---|---|---|---|
| 0 | 18,000 | 8,000 | 12,000 | 30 |
| T4 | 35,000 | 21,000 | 24,000 | 65 |
| T6 | 45,000 | 40,000 | 30,000 | 95 |

properties (Table 3). As the table shows, solution heat-treated tempers (T4 and T6) provide significantly higher strength and hardness.

## Milling Application

Contemporary indexable-insert cutters can mill the majority of wrought aluminum alloy grades—except the 4xxx series group containing 4 to 13 percent silicon as the principle alloying element—at cutting speeds from 4,000 to 6,000 sfm. Selecting the cutting speed and other machining parameters, such as axial DOC, radial WOC and feed per tooth, are based on the toolmaker's recommendations and an end user's milling experience.

Typically, selection of the cutting parameters is based on the type of aluminum alloy (wrought or cast) and the amount of silicon content. Unfortunately, little or no attention is paid to specific tempers applied to various aluminum alloys. Because tempers affect an alloy's strength and hardness, end users must have this information to achieve maximum productivity when milling aluminum alloys.

Without a doubt, there are plenty of aluminum alloys to choose from. The three groups briefly described in this article—out of the seven groups defined by the principal alloying element—contain 127 grades of aluminum alloys. Keeping in mind that each grade is produced to several tempers and each temper is characterized by different mechanical properties, there is enormous availability of grade-temper aluminum alloys.

By understanding the composition of aluminum alloys, end users can be more confident in selecting the appropriate grades and cutting parameters to maximize productivity. △

## About the Author

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