# FORMABILITY AND STRENGTHENING MECHANISMS OF Al-ALLOYS FOR COLD DEEP DRAWING PROCESS

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## 1. Introduction

The increasing demands for lightweight design in the transport industry have led to an extensive use of lightweight materials such as aluminum (Al) and its alloys. The forming of Al sheets, however, presents significant challenges due to the low formability and the increased susceptibility to friction. The formability of a blank during the deep drawing is depends on the process parameters such as blank holder force, lubrication, punch and die radius, die-punch clearance, in addition to mechanical properties and thickness of the sheet metal and part's geometry. The drawing of metal or deep drawing is the process by which a punch force is applied to sheet metal to flow between the surfaces of a punch die. By this, the sheet is formed into cylindrical, conic, or box-shaped parts. A schematic illustration of these deep drawing processes is shown in Figure 1. For this process, the basic tools are the punch, the drawing die ring, and the blank holder.

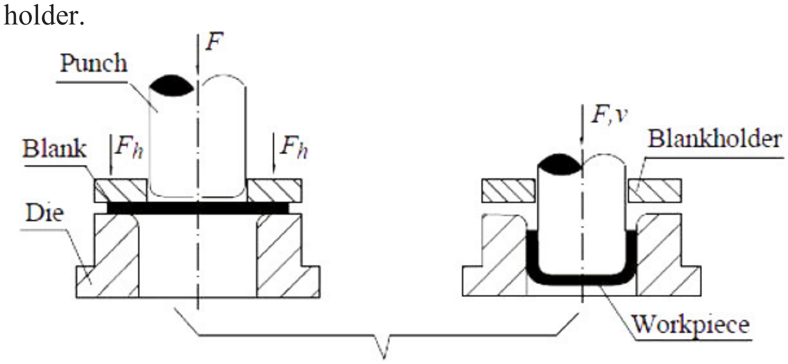


Figure 1: Schematic illustration of deep drawing process.

Figure 2 shows the important process parameters involved in the deep drawing process. In addition, material properties such as the strain hardening coefficient (n) and normal anisotropy (R) affect the deep drawing operation.

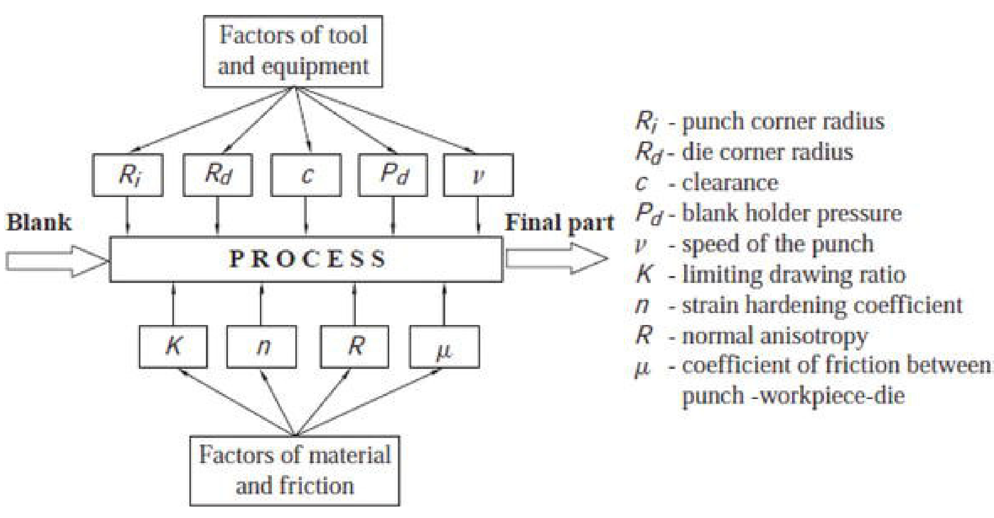


Figure 2: Significant variables in deep drawing.

To establish the geometry of a part, it is essential to know the limit to which the part material can be formed without reaching failure. This forming limit depends, in addition to the shape change and process conditions, on the ability of a material to deform without failure. The limit drawing ratio (LDR) is commonly used to provide a measure of the drawability of sheet metal. For the deep drawing quality steels have a high *r*-value in the range of 1.5–2.2; while most of the aluminum alloys have an *r* value between 0.7 and 1.0. Even though the *r* values for the aluminum alloys are only about half that of steel, they have quite satisfactory drawing behaviour. Aluminum alloys are majorly categorized as 1xxx, 2xxx, 3xxx, 4xxx, 5xxx, 6xxx, 7xxx, and 8xxx based on major alloying elements.

The elements that are most commonly present in commercial alloys to provide increased strength—particularly when coupled with strain hardening by cold working or with heat treatment, or both—are copper, magnesium, manganese, silicon, and zinc (Figure 3). These elements all have significant solid solubility in aluminum, and in all cases the solubility increases with increasing temperature (Figure 4).

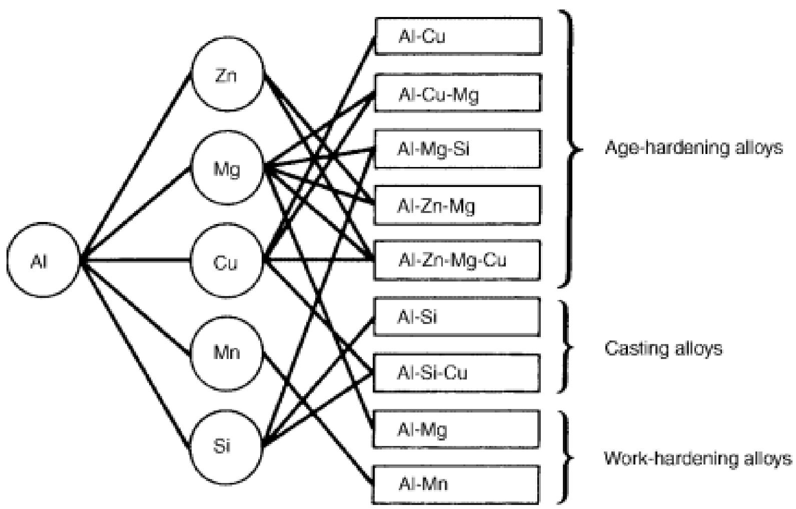


Figure 3: The principal aluminum alloys.

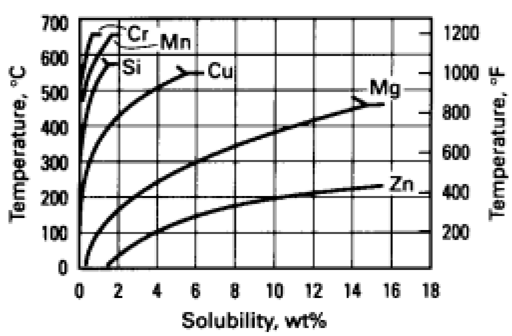


Figure 4: Equilibrium binary solid solubility as a function of temperature for alloying elements most frequently added to aluminum.

Table 1 shows the maximum nominal yield and tensile strengths for the different alloy families and the methods by which the strength is increased. There is a wide range of strengths possible with aluminum alloys. The yield and tensile strengths possible in the different alloy families depends on the strengthening mechanisms available.

Table 1: Yield and tensile strengths Al-alloys

| Alloy series | Methods for strengthening aluminum | Yield Strength ksi (MPa) | Tensile Strength, ksi (MPa) |
|---|---|---|---|
| 1xxx | Cold-working | 4-24 (30-165) | 10-27 (70-185) |
| 2xxx | Cold-working, Precipitation | 11-64 (75-440) | 27-70 (185-485) |
| 3xxx | Cold working, solid solution, dispersion | 6-36 (40-250) | 16-41 (110-285) |
| 4xxx | Cold working, dispersion | 46 (315) | 55 (380) |
| 5xxx | Cold working, solid solution | 6-59 (40-405) | 18-63 (125-435) |
| 6xxx | Cold working, precipitation | 7-55 (50-380) | 13-58 (90-400) |
| 7xxx | Cold working, precipitation | 15-78 (105-540) | 33-88 (230-605) |

## 2. Cold Working

Cold working involves the reduction in thickness of a material. All aluminum alloys can be strengthened by cold working. During the cold working, the strength of a metal increases due to the increase in the number of dislocations in the metal compared to its pre-cold-worked condition. Dislocations are defects in the arrangement of atoms within a metal. The increase in the number of dislocations due to cold working is responsible for the increase in strength. Pure aluminum at room temperature has yield strength of 4 ksi (30 MPa). In the fully cold-worked state the yield strength can be as high as 24 ksi (165 MPa).

### 3.1 Cold Deep Drawing of 1XXX Al-alloys

Aluminum of 99 percent or higher purity has many applications, especially in the electrical and chemical fields. Excellent corrosion resistance, high thermal and electrical conductivity, low mechanical properties and excellent workability characterize these compositions. Among 1XXX series, 1050, 1060, 1100 and 1350 aluminum are popular alloys for general sheet metal work where moderate strength is required.

Alloy 1050 is typically used for general sheet metal work, architectural flashings, cable sheathing, chemical processing plant equipment, vessels, appliances, lamp reflectors and food industry containers. Alloy 1060 has excellent forming capability by cold or hot working with commercial techniques. Applications include chemical and food handling equipment, as well as for food, pharmaceutical and liquid containers. Alloy 1100, although slightly stronger than alloy 1060, shares some of the same applications, plus fin stock, spun hollowware, impacted fire extinguisher bottles and tubing. This alloy contains slight additions of silicon, iron, and copper for strength. Alloy 1350 is used primarily for electrical conductors, and H111 temper exhibits the highest electrical conductivity of all extruded aluminum conductor grades, meeting or exceeding 61.0% IACS.

### 3.2 Cold Deep Drawing of 2XXX Al-alloys

Copper is the principal alloying element in this group often with magnesium as secondary addition. These alloys require solution heat-treatment to obtain optimum properties. In some instances artificial aging is employed to further increase the mechanical properties. This treatment materially increases yield strength, with attendant loss in elongation. Its effect on tensile strength is not so significant. The alloys in this series do not have as good corrosion resistance as most other aluminum alloys, and under certain conditions they may be subject to inter-granular corrosion.

The cold forming of heat-treatable, high-strength aluminum alloys such as Al-Mg alloys in the naturally aged (T4) or precipitation-hardened (T6) state is usually limited by poor formability. The high internal residual stresses in these alloys give rise to a large elastic recovery, known as springback, and a resulting deviation from the desired shape after the workpiece is released from the die. The resulting low-dimensional accuracy is the main reason why the application of high-strength aluminum alloys has been limited in the automotive industry. To overcome these drawbacks, the cold-forming step in heat-treatable aluminum alloys can be carried out before aging.

### 3.3 Cold Deep Drawing of 3XXX Al-alloys

Manganese is the major alloying element of alloys in this group, which are generally non-heat-treatable. Because only a limited percentage of manganese, up to about 1.5 percent, can be effectively added to aluminum, it is used as a major element in only a few instances.

The 3xxx series alloys would be particularly favored for applications that demand complex geometries featuring gentle curves and nuanced bends. Moreover, the 3xxx Al-alloys, when subjected to H32 tempering, exhibit a balance between strength and formability, which is favorable in the realm of deep drawing applications. Among various Al alloy, AA3003 alloy is most widely used for making kitchen utensils. Fe, Mn and Si are the major alloying elements in AA3003 alloy.

### 3.4 Cold Deep Drawing of 4XXX Al-alloys

The major alloying element of this group is silicon, which can be added in sufficient quantities (up to 12%) to cause substantial lowering of the melting point without producing brittleness in the resulting alloys. For these reasons aluminum-silicon alloys are used in welding wire and as brazing alloys where a lower melting point than that of the parent metal is required.

### 3.5 Cold Deep Drawing of 3XXX Al-alloys

Magnesium is one of the most effective and widely used alloying elements for aluminum. When it is used as the major alloying element or with manganese, the result is a moderate to high strength non-heat-treatable alloy. Alloys in this series possess good welding characteristics and good resistance to corrosion in marine atmosphere.

### 3.6 Cold Deep Drawing of 6XXX Al-alloys

Alloys in this group contain silicon and magnesium in approximate proportions to form magnesium silicone, thus making them heat-treatable. Though less strong than most of the 2xxx or 7xxx alloys, the magnesium-silicon alloys possess good formability and corrosion resistance, with medium strength.

### 3.7 Cold Deep Drawing of 7XXX Al-alloys

Zinc in amounts of 1 to 8% is the major alloying element in this group, and when coupled with magnesium and copper (or without copper) results in heat-treatable alloys of very high strength. Usually other elements such as manganese and chromium are also added in small quantities. The out-standing member of this group is 7075, 7050 and 7049, which is among the highest strength alloys available and is used in air-frame structures and for highly stressed parts.

### 3.8 Cold Deep Drawing of 8XXX Al-alloys

8XXX Al alloys have limited applications in the sheet metal forming. Aluminum alloy AA8011 which is generally used for household foil is an attractive material due to the fact that it can provide a suitable combination of strength and ductility. The principal strengthening agents in AA8011alloy are the Fe-Si constituent particles. These particles are capable of stabilizing fine grain or sub-grain structure which can develop interesting combinations of strength and ductility.

## 4. Strengthening Mechanisms

In aluminum alloys, four major mechanisms are known: solid-solution strengthening, precipitation strengthening and dispersion strengthening.

### 4.1 Solid Solution Strengthening

Certain alloying elements added to aluminum mix with the aluminum atoms in a way that results in increased metal strength. This mixture is called a solid solution because the alloying atoms are mixed in with the aluminum atoms. This is discussed in detail in Principles of Metallurgy and Aluminum Metallurgy. The extent of strengthening depends on the type and amount of the alloying elements. Manganese and magnesium are examples of elements added to aluminum for the purpose of strengthening. Solid solution strengthening occurs in 3xxx and 5xxx alloys through the addition of manganese (3xxx) and magnesium (5xxx) to aluminum.

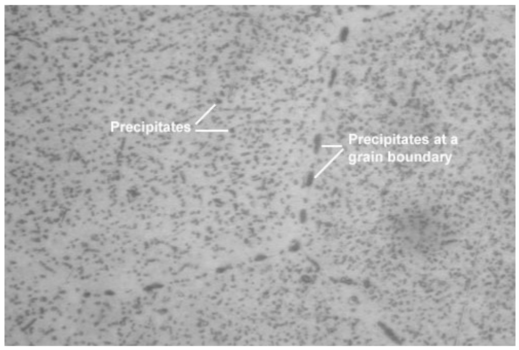


Figure 3: Precipitates in Al-Cu alloy.

### 4.2 Precipitation Strengthening

With precipitation strengthening, particles less than 0.001 mm in diameter form inside the metal. These particles are called precipitates and consist of compounds of aluminum and alloying elements or compounds of the alloying elements. This figure 3 shows Al-Cu precipitates in an Al-Cu alloy. Precipitates form as a result of a series of heat treating processes. The step of the process during which precipitates form is called aging. Precipitation strengthening can increase the yield strength of aluminum from about five times up to about fifteen times that of unalloyed aluminum. The strength depends on the specific alloy and the aging heat treatment temperature. Only certain alloys can be precipitation strengthened. The 2xxx, 6xxx, and 7xxx alloys can be precipitation strengthened through the formation of Al-Cu (2xxx), Mg-Si (6xxx), and Al-Zn-Mg-(Cu) (7xxx) precipitates. The 1xxx, 3xxx, 4xxx, and 5xxx alloys cannot be precipitation strengthened.

### 4.3 Dispersion Strengthening

Dispersoid particles form during the aluminum casting process when manganese in 3xxx series alloys reacts with aluminum and iron and silicon. These particles are less than 0.001 mm in diameter. Dispersoid particles influence the grain structure that forms during heat treating so that there is increased strength compared to an alloy without dispersoids. Fully-annealed 1100 aluminum has tensile strength of 13 ksi and yield strength of 5 ksi. Fully-annealed 3003 has minimum tensile strength of 16 ksi and minimum yield strength of 6 ksi. This increase in strength is due to the grain structure formed as a result of the presence of dispersoids.

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