Forming Characteristics of Coarse and Fine-Grained AA 2024 Aluminum Alloy Sheet

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The forming behavior of Al-Cu-Mg-Mn alloy 2024 sheet with fine, equiaxed and coarse, elongated grain structures was characterized in the O temper (fully annealed) and W temper (solution heat treated and quenched) conditions. The fine-grained materials had better biaxial stretching capabilities in both tempers. The fine-grained O temper also had superior drawing and plane-strain stretching properties. For the O temper, conventional tensile forming indicators such as elongation and strain ratio correlated with ball punch depth, forming limit strains, and limiting draw ratio. Such correlations were not apparent in the W temper, however, nor could the two tempers be compared on the basis of tensile data alone.

Keywords

Al-Cu-Mg-Mn alloy sheet, biaxial stretching, formability, forming limit strain, grain size, temper effects, tensile elongation

1. Introduction

ALLOY AA 2024 (nominally Al-4.2Cu-1.5Mg-0.5Mn) normally is used in the solution heat treated and aged T temper. However, fabricated sheet parts often are formed in the softer, fully annealed (O temper) or freshly solution heat treated (W temper) conditions. O temper components are subsequently heat treated; those made from the W temper are naturally or artificially aged to the desired T42 or T62 condition after forming. O temper material has the advantage of being stable, i.e., its properties do not change with time at room temperature, but subsequent heat treating and quenching operations often introduce distortion problems. Although forming in the W temper circumvents the distortion concern, sheet in this condition hardens as it naturally ages, so the delay time between solution heat treating and forming must be minimized. Alternatively, the material can be stored in a freezer until it is ready to be formed.

Although alloy 2024 sheet has been used for about six decades, its forming behavior in the O and W tempers has received surprisingly little attention, except for a few forming limit[1,2] and limiting draw ratio[2,3] evaluations. Furthermore, scant attention has been given to the effects of grain structure, which is highly dependent on fabricating parameters such as cold work, annealing time/temperature, and heating rates. For example, the conventional O temper, which is normally batch annealed, has a relatively coarse elongated grain structure. Continuously annealed sheet, on the other hand, is typified by finer, more equiaxed grains. These variations in grain structure can influence forming characteristics. A well-known phenomenon, for example, is the rough "orange peel" surface appearance common to coarse-grained sheet. Less understood, though, are the effects that grain structure can have on other measures of formability, such as tensile ductility, limiting draw ratio, width-to-thickness strain ratio, biaxial stretching capability, forming limit strains, etc.

Many of the continuum approaches to sheet metal formability ignore microstructural features such as grain size and aspect ratio.[4] These factors have been receiving more attention over the past 10 to 15 years, however. Wilson and colleagues,[5] for example, showed that the limit strains in biaxial stretching vary systematically with the ratio of sheet thickness to grain size, whereby inhomogeneous strain due to the anisotropy of individual grains or groups of grains leads to localized necking. These effects previously had been predicted[6] by a theoretical Marciniak-Kuczynski (M-K) analysis of the surface roughness determined as a function of grain size and strain.

The following compares the forming characteristics of conventional coarse-grained (CG) 2024 sheet with those of a fine-grained (FG) Hi-Form™ product.*

2. Materials and Procedures

A number of 1.6 to 1.8 mm thick commercially produced lots of each type of sheet (FG and CG) were tested for:

- Tensile elongation in three directions, ASTM E8
- *R* value (ratio of width to thickness strain), ASTM E517
- *n* value (strain-hardening exponent), ASTM E646
- Limiting draw ratio
- Ball punch depth, ASTM E643
- Forming limit strains

Most of these tests were applied to both the as-processed O temper and to the W temper, which was obtained by solution heat treating O temper sheet at 495 °C for 15 min followed by a quench in 20 °C water. For the latter condition, delay times between heat treating and testing ranged from 1 h to 2 weeks.

The tensile elongations, *R* values, and *n* values were measured on 12.7-mm wide specimens with a 51-mm gage length. Ball punch depths were determined under well-lubricated conditions: petroleum jelly for the 22-mm ball punch (Olsen test) and petroleum jelly plus polyethylene film for the 47-mm ball. The limiting draw ratios were conducted with a 33-mm punch. Forming limit diagrams were determined by measuring minor and major strains on transverse (90° to rolling direction) speci-

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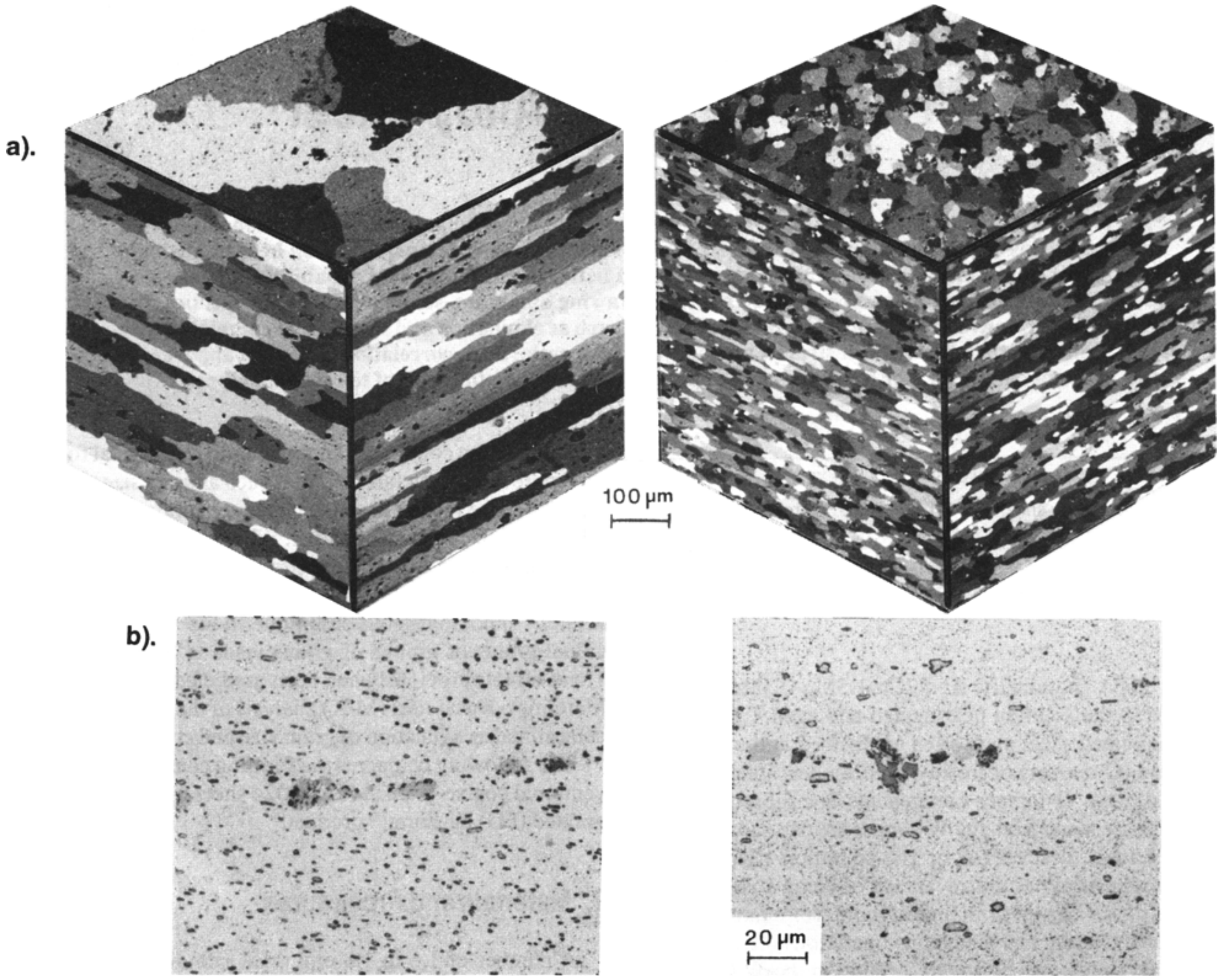

Fig. 1 Microstructures of coarse- and fine-grained 2024 sheet. (a) W temper, Barker's etch/polarized light. (b) O temper, dilute Keller's etch.

mens of various widths, which were deformed over a 47-mm diameter ball punch.

An optical imaging system was used to measure the strains on electro-etched circles (initially 2.5-mm diameter) to an estimated accuracy of ±0.05 mm (±2% strain). Forming limit strains were measured on O temper sheet only; because the W temper is unstable, separate diagrams would be needed for various delay times. Forming limit diagrams determined on "fresh" W (15-min delay) and T3 temper sheet can be found in Ref 2 (grain structure unspecified).

Typical microstructures of the two types of material are shown in Fig. 1. The conventional CG sheet had elongated pancake-shaped grains about 0.05 mm thick with a longitudinal aspect ratio of 15:1. Grains in the FG sheet were much smaller (0.01 to 0.02 mm thick) and more equiaxed (~2 to 3:1 aspect ratio). The ratios of sheet thickness to grain thickness were about 25:1 and 100:1, respectively. The only other microstructural difference of note was a coarser dispersion of $CuAl_2$ and $CuMgAl_2$ precipitates in the CG O temper sheet (these optically visible precipitates were not present in the W temper). Both materials contained relatively large insoluble Al_7Cu_2Fe constituents, which were aligned in the rolling direction.

3. Results

3.1 *O Temper Sheet*

3.1.1 Tensile Properties

Elongation for the three test directions (0° longitudinal; 45 and 90° transverse) are plotted against yield strength in Fig. 2. Lot-to-lot variability contributed to considerable scatter, but as expected, there was a general trend for elongation to decrease with increasing strength. The CG sheet had chisel-point fractures in all orientations, as did those for the 45° direction in the FG material. The 0 and 90° directions in the FG sheet had shear-type fractures. When the averaged elongations for each of the three directions were compared, as shown in Table 1, it became apparent that the FG sheet was more isotropic, with significantly higher 90° elongation than the CG material. This finding was also reflected in the averaged R values (width-to-thickness strain ratio) measured at 12% strain, as shown in Table 2. Although both materials had high strain ratios in the 45° direction (relative to 0 and 90°), as has been observed previously,[7] the FG sheet was more isotropic as defined by $\Delta R = (R_0 + R_{90} - 2R_{45}) / 2$; the R values in all directions were also higher in the FG material, giving a significantly greater R_{avg}. The work-hardening index, n, defined by the relation $\sigma = k\varepsilon^n$, where σ is the flow stress at strain ε, and k is a constant, was slightly higher in the CG materials (0.31 versus 0.29) and was not orientation dependent.

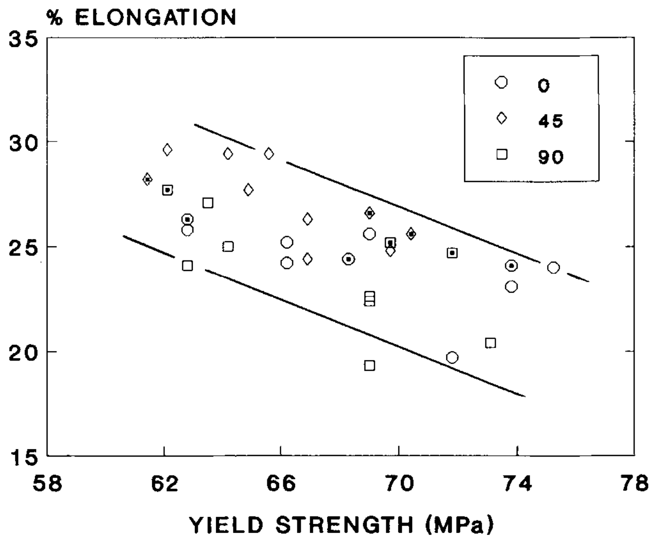

Fig. 2 Strength-elongation relationships for O temper sheet. Open symbols, coarse grain; closed symbols, fine grain.

3.1.2 Limiting Draw Ratio

In view of the higher R values for the FG sheet, it might be expected to have better deep-drawing characteristics as well. For confirmation, the limiting draw ratios (LDRs) of two sheet specimens were determined by drawing blanks of various sizes (70, 73, and 76 mm) through a 36.3-mm die using a 33-mm punch (all dimensions are diameters). The maximum (limiting) draw ratios and the relevant sheet properties are listed in Table 3. In spite of a lower tensile elongation (and higher strength), the FG material had a somewhat greater LDR. Anisotropy, as measured by cup earing, was also lower in the FG sheet, as would be predicted from its lower ΔR value (–0.13 versus –0.18).

3.1.3 Ball Punch Depth

Maximum cup depths drawn with the Olsen 22-mm diameter punch (a measure of biaxial stretching capacity) are compared in Fig. 3, which shows that cup depth correlates with transverse (90°) elongation. The correlation with transverse elongation was better than that with the average value, because fractures generally occurred parallel to the rolling direction, especially in the CG materials. However, the data for the FG materials are grouped above for those for the standard CG sheet. A few tests were also conducted with a 47-mm diameter punch under well-lubricated conditions; in this case, cup depths ranged from 20.3 to 20.7 mm and 18.3 to 19.3 mm for the FG and CG sheet, respectively. Notably, the latter materials also had much rougher surfaces, as shown in Fig. 4. Metallographic

Table 1 Tensile elongations for coarse and fine-grained 2024-O sheet

	Elongation, %, at:			
Material	**0°**	**45°**	**90°**	**Avg(a)**
CG	23.9	27.7	23.2	25.6
FG	24.7	26.6	25.7	25.9

(a) Average = (0° + 90° + 2 × 45°) ÷ 4

Table 2 Width-to-thickness strain ratios for coarse- and fine-grained 2024-O sheet

	R value at:				
Material	**0°**	**45°**	**90°**	**Avg**	**ΔR**
CG	0.51	0.64	0.42	0.55	–0.18
FG	0.58	0.68	0.53	0.62	–0.13

Table 3 Drawing properties of fine- and coarse-grained O temper sheet

	Earing			Average yield	Average
Material	**LDR**	**%**	**R_{avg}**	**strength, MPa**	**elongation, %**
CG	2.12	3.5	0.56	62.8	28.0
FG	2.21	2.5	0.64	71.4	25.0

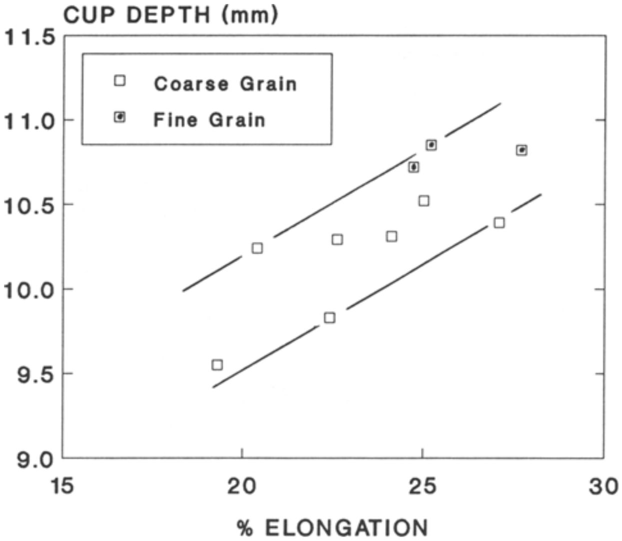

Fig. 3 Relationship between Olsen cup depth and transverse tensile elongation for O temper sheet. Open symbols, coarse grain; closed symbols, fine grain.

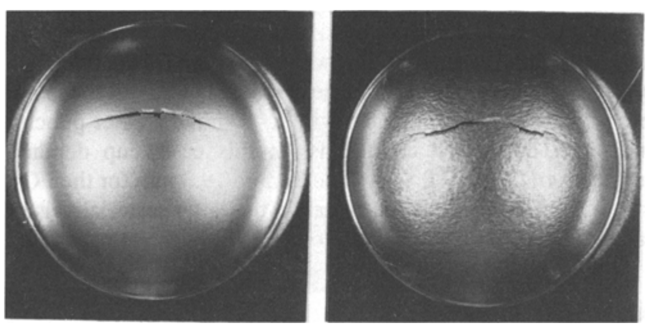

Fig. 4 Surfaces of 47-mm ball punch impressions in FG (left) and CG (right) sheet.

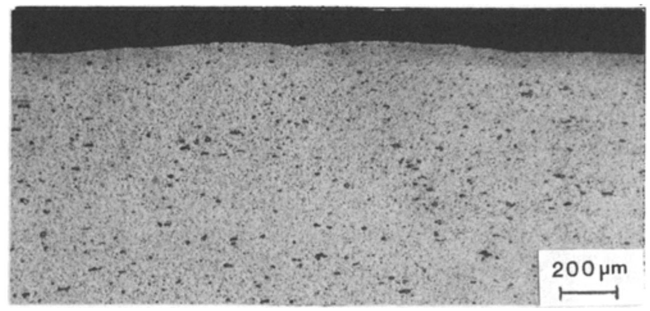

Fig. 5 Transverse section through dome in CG O temper sheet showing surface undulation.

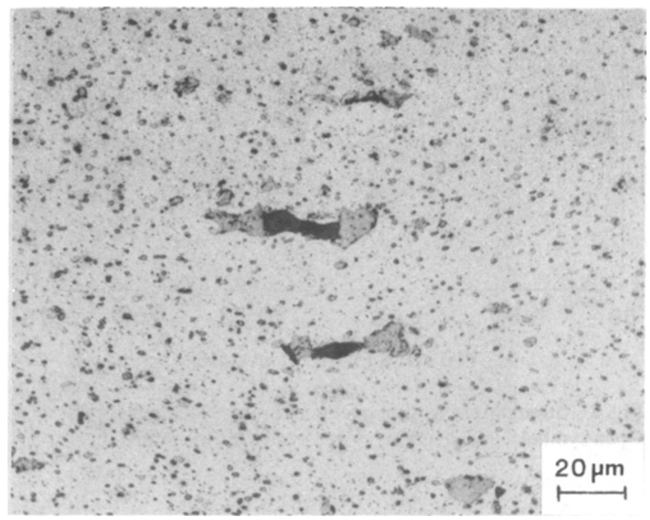

Fig. 6 Cavitation associated with Al_7Cu_2Fe constituents in the necked region of the CG O temper dome.

examination of a transverse cross section perpendicular to the fractures through a CG dome showed a wavy surface (Fig. 5) with a periodicity of 0.75 to 1.0 mm, which is considerably larger than the grain width as viewed in a surface plane (≅0.2 mm, see Fig. 1).

The ratio of the reduced thickness to the "normal" sheet thickness for grooves nearest the neck was about 0.98; within the neck, the ratio was about 0.94. There were no such surface waves apparent in the FG sheet. Higher magnification views in the severely necked region revealed cavitation at broken Al_7Cu_2Fe constituents (Fig. 6). Although this phenomenon may have contributed to the final fracture process, it appeared to play no role in the initiation of necking. Similar cavities were also found in the necked region of the domes formed from the FG sheet.

3.1.4 Forming Limit Diagrams

Major and minor strains measured on "safe" and necked regions of the stretched domes are shown in Fig. 7 and 8. The FLD was taken to be the upper bound of the "safe" data points.

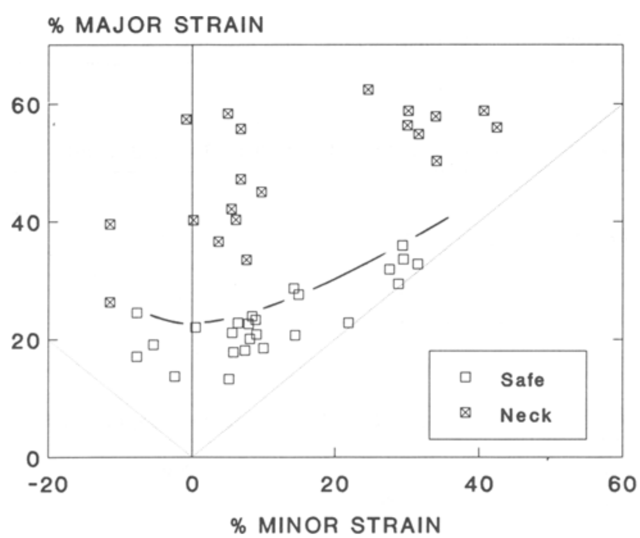

Fig. 7 Forming limit diagram for coarse-grain O temper sheet.

Table 4 Tensile properties of fine- and coarse-grained W temper sheet (1-day delay)

Test direction	UTS, MPa	YS, MPa	Elongation, %	R
Coarse grain				
0°	468	277	26.7	0.57
45°	444	264	27.6	0.64
90°	452	273	27.2	0.55
Avg	452	270	27.3	0.60
Fine grain				
0°	460	295	25.7	0.61
45°	459	278	27.2	0.77
90°	456	277	26.5	0.72

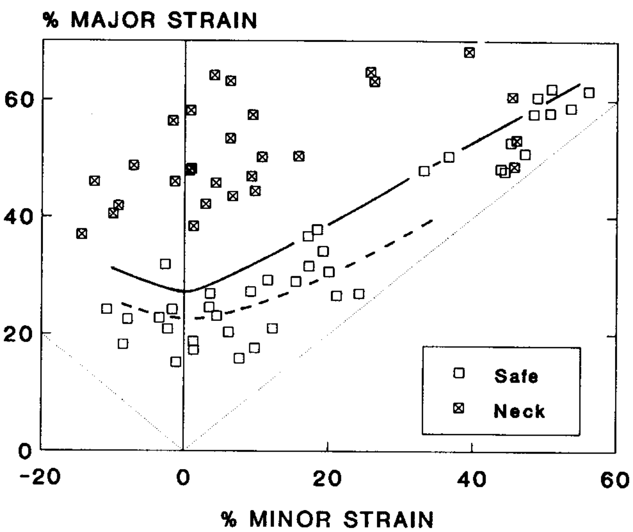

Fig. 8 Forming limit diagram for fine-grain O temper sheet. Dashed line represents limit strains for coarse-grain sheet.

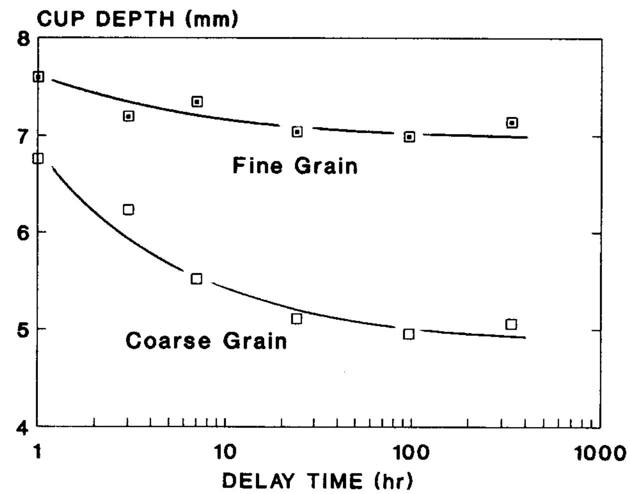

Fig. 9 Effect of delay time after heat treating on Olsen cup depth of W temper sheet.

It is apparent that FG sheet can accommodate higher strains under biaxial (+ minor strain) and plane-strain stretching conditions than CG sheet. This perhaps explains the large difference in forming limit strains for two lots of 2024-O reported previously.[1]

3.2 *W Temper Sheet*

3.2.1 Tensile Properties

Tensile property data obtained 24 h after solution heat treating and quenching showed little difference in strength or elongation, but R values were again significantly greater in the FG sheet (see Table 4), suggesting better drawing characteristics. Work-hardening coefficients ranged from 0.19 to 0.20, with no apparent dependency on grain structure or test direction. Although reductions in area were not measured, they were obviously lower than those for the O temper. Also, all of the fractures were of the shear type in both FG and CG sheet.

3.2.2 Limiting Draw Ratio

In two attempts to draw 55-mm blanks from each sheet 120 to 136 min after quenching, only one CG sample was successful. The LDRs in this condition are therefore ≤1.67.

3.2.3 Ball Punch Depth

Maximum cup depths and loads at fracture were measured with the 22-mm ball as a function of delay time after quenching. As Fig. 9 shows, the FG material has a definite advantage: cup depths were much greater, and the margin improved with increasing delay time. These benefits extend the allowable forming time and minimize the need for refrigeration prior to forming. Notably, there were also remarkable differences in the maximum load at fracture (Fig. 10), with the CG material showing a decrease with time, whereas the load for FG sheet increased with time.

4. Discussion

The foregoing results have shown that fine-grained 2024 sheet in both the O and W tempers has better forming behavior than coarse-grained sheet, as characterized by a number of

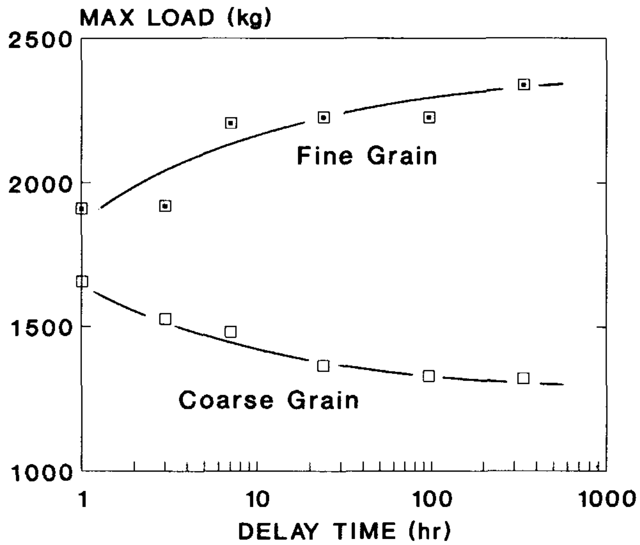

Fig. 10 Maximum ball punch load versus delay time for W temper sheet.

laboratory tests. A decade of production experience also supports this contention. It may be instructive to make correlations between some of the properties that were measured, especially as they relate to a comparison of the two tempers.

As already noted, there was a fairly good relationship between Olsen cup depth and tensile elongation for the O temper materials (Fig. 3). Such correlations have been reported for a number of alloys[8] and for a variety of materials tested with a dry 102-mm ball punch.[9] Notably, the FG and CG materials had essentially the same tensile *n* value, which would suggest equal stretching behavior. Previous correlations for nonferrous materials generally have been unsatisfactory; however, because as pointed out by Ghosh and Backofen,[10] the *n* value can change under biaxial stress states. Nor were differences in the forming limit diagrams reflected by the *n* values. Other work has shown that the plane-strain intercept of the FLD for steel is proportional to *n* only up to a value of 0.2.[11] Further increases have little effect on the position of the curve. Tensile elongation may be a better predictor of the FLD, at least in the plane-strain region, because Stevenson[12] has shown a good correlation between this property and limiting dome height. In any case, grain size may be more important in controlling limit strains in the biaxial regime than are the macroscopic flow stress or strain anisotropy factors.[13]

For O temper sheet, there was a positive relationship between *R* value and limiting draw ratio, as could be expected. The higher *R* values of the FG materials, however, did not detract from their biaxial stretching capabilities as might be predicted.[12-15] It is also apparent that *R* values are not a unique predictor of drawability because the W temper sheet had higher width to thickness strain ratios than the O temper, yet their LDRs were greatly different <1.65 and ~2.2, respectively). This is contrary to the results of Logan et al.[3] whose LDR measurements on a wide variety of sheet materials (including 2024-T4) were all greater than 2.1 for strain ratios as low as 0.6. Perhaps the discrepancy is due to differences in sheet thickness (~1.6 versus 0.9 mm) and/or punch diameter (23 versus 50 mm). The data are in better agreement with the results of Romhanji et al.,[2] who measured an LDR of 1.82 on fresh 1.0 mm thick W temper sheet, using a 33-mm punch. Nevertheless, a difference in drawing behavior between the O and W tempers is evident; factors other than strain ratio, such as yield strength and *n* value, must also be important.

Another notable difference between the two temper conditions was their ball punch depths, in spite of almost identical tensile elongation. Also, the large difference between the FG and CG Olsen cup depths in the W temper was not reflected by tensile elongation (as it was in the O temper) or any of the other tensile formability indicators. Especially intriguing is the W temper Olsen cup behavior where the maximum load for the FG sheet increased with delay time whereas the CG load decreased. Because the yield and ultimate strengths increase with delay time, an increase in maximum load would be expected, provided the cup depth remains approximately constant. However, if failure occurs at ever-decreasing cup depths, then a decreasing peak load might also be expected, as observed in the CG material.

The ratios of sheet thickness to grain size (in the through-thickness direction) in this study averaged about 25:1 and 100:1 for the CG and FG sheet, respectively. Studies on other metals have shown that grain size has the greatest effect on limiting strains in biaxial stretching at ratios below 30:1.[5] However, the grains in the CG material evaluated in this study had a large aspect ratio, i.e., the sheet thickness was less than ten times the grain width, so this could be a significant factor in reduced formability. For sheet thickness to grain size ratios of 10 to 30, an M-K analysis[6] predicts reduced thickness ratios of 0.92 to 0.96, respectively, for instability under biaxial stretching conditions. These values compare with apparent ratios of 0.94 to 0.98 measured in this study on the CG material. Note, however, that a sheet "imperfection" is not required to initiate localized necking in out-of-plane stretching because of the strain gradients present as a result of geometrical and friction effects in punch forming.[16]

In summary, grain structure has a pronounced effect on the forming behavior of 2024 alloy sheet in both the O and W temper conditions. For the O temper, some of the conventional relationships and correlations between various forming indicators appear to apply, e.g., ball punch depth and tensile elongation, *R* value, and LDR. However, they are not as well obeyed as the W temper, nor can the forming characteristics of the two tempers be compared on the basis of these "established" relationships.

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