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PROCESSING AND PERFORMANCE OF Al-Li-Cu-X EXTRUSIONS

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ABSTRACT

The extrusion characteristics of 2090 (Al-Cu-Li) and 8090 and 8091 (Al-Li-Cu-Mg) alloys from the standpoints of ease of extrusion and compatibility with plant operations were investigated. Experimentation was conducted to determine the effects of extrusion temperature and extrusion rate on extrudability and product performance. Structure studies were carried out to explain variations in mechanical properties.

Experimental extrusion limit diagrams for Al-Li-Cu and Al-Li-Cu-Mg alloys showed that the addition of magnesium lowered the working range by increasing the flow stress and enhancing the onset of incipient melting and surface tearing, particularly at the higher alloying levels. Plant trials were conducted with 2090 alloy. The extrudability of this alloy was more similar to 6061 alloy from the standpoints of press effort and run out speed than to the conventional 2XXX and 7XXX aircraft alloys.

The mechanical properties of the extrusions were a function of microstructure and test direction. High longitudinal ultimate tensile and yield strength (>600 MPa) and good toughness were obtained in the peak strength condition when the extrusions had fibrous, elongated grains. Transverse strengths and toughness were substantially lower. Material with a more recrystallized, equiaxed grain structure showed less variation with test direction, but significantly lower strengths were obtained.

It was concluded that 2090, 8090 and 8091 alloys can be extruded using conventional equipment and methods. Alloy 2090 is easier to extrude than the Mg-bearing compositions. The mechanical properties of these alloys are very structure sensitive, which can be controlled to some extent by the extrusion parameters.

INTRODUCTION

There has been a virtual explosion of published information concerning Al-Li alloys since 1980 when the First International Aluminum-Lithium Conference was held (1-3). However, the bulk of information has been related to the physical metallurgy and properties of the alloys. In order to gain confidence in Al-Li alloys, the effects of variations in processing must be better understood and the information disseminated. Earlier papers covered the effects of processing variations on the properties of Al-Li-Cu and Al-Li-Cu-Mg alloy plate (4,5). The present paper discusses the extrudability of Al-Li-Cu-Mg) alloys. The relationships between processing conditions and extrusion properties were examined along with the compatibility of Al-Li alloy extrusion with current plant procedures.

EXPERIMENTAL PROCEDURES

The bulk of the material used in the laboratory trials was DC cast as 20 x 40
cm rectangular ingots from which 7.5 cm diameter by 23 cm long extrusion billets were machined. A limited number of billets were machined from 10 x 20 cm rectangular permanent mold ingots. Alloys 2024 and 6061, which were extruded for comparison, were DC cast as 7.5 cm diameter logs. The 2090 billets extruded in plant trials were DC cast either at Reynolds Metals as 35 cm diameter billet or at Kaiser Aluminum as 40 cm diameter billet. The alloys were homogenized based on practices previously developed by Ashton et al. (4,5) for rolling ingots; these practices were 24 hours at 541°C for 2090 and 8090 and 24 hours at 532°C for alloys 2091 and 8091.

The laboratory extrusions were produced using a 640 ton direct press with a 8.25 cm diameter container. The billets were preheated in a circulating air furnace at 524-537°C and extruded at 385-524°C with the container temperature typically 42-56°C below the billet temperature. Extrusion ratios ranged between 10/1 and 64/1 and ram speeds were varied from 15-56 cm per minute. All the extrusions were fan cooled. Except for a limited number of rectangular sections extruded for comparison with 2024 and 6061 alloys, all of the laboratory extrusions were produced as round rod.

The solution heat treatment practices used were 30 minutes at 541°C for 2090 and 8090 and 30 minutes at 532°C for 8091. All the extrusions were cold water quenched and stretched 5%. Aging practices used to develop underaged and near peak aged properties are given in Table 1 for the various alloys.

Longitudinal tension tests were performed on laboratory extruded material using standard and subsize ASME B 557 threaded-end round specimens. The tension specimen size depended upon the original rod diameter, with the largest compatible specimen used in each instance. A limited number of tension tests were also performed on full Section rod samples. Toughness testing was performed on the 1.75 cm and 2.5 cm rod using subsize threaded-end 1.27 cm sharp-notch tensile specimens (ASME E 602).

Tension tests on the plant produced extrusions were performed in both the longitudinal and transverse directions using either rectangular or round specimens. Toughness testing was performed in the L-T and T-L directions using sharp-notch (<0.001 inch radius) Charpy impact specimens (Modified ASME E 23).

RESULTS AND DISCUSSION

LABORATORY TESTING

Al-Li-Cu Alloy

During initial laboratory trials a series of 2090 billets was extruded under a range of processing conditions which included variations in extrusion ratio, ram speed and billet temperature. A series of curves of peak extrusion pressure versus billet temperature was developed and are shown in Figures 1 and 2. Peak pressure varied directly with extrusion ratio and ram speed and inversely with billet temperature, which is consistent with data reported by others for both conventional and Al-Li-X alloys (6,7).

The range of conditions under which an alloy can be extruded is governed by the available pressure of the press and by the susceptibility of the alloy to incipient melting and surface tearing. Extrusion limit diagrams can be developed, using these two limiting factors, which indicate the potential range of processing conditions. This range may be further limited by the need or desire for specific structures, mechanical properties or additional processing limitations. Amlbe and Stenger (8) have shown a generalized example of these limit diagrams, and experimental limit diagrams for Al-Li-Mg and Al-Li-Mg-Cu alloys have been developed by Parson and Sheppard (9).

A similar limit diagram was developed for 2090 alloy as shown in Figure 3. Increasing either the extrusion ratio or the ram speed reduces the acceptable range of extrusion temperatures by increasing the pressure or increasing the
Table 1. Aging Practices

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<td>8091</td>
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Figure 1. Effect of Extrusion Ratio on the Peak Pressure of 2090 Alloy Extrusions.

Figure 2. Effect of Ram Speed on Peak Pressure of 2090 Alloy Extrusions.

Figure 3. Experimental Extrusion Limit Diagram -- 2090 Billet

Figure 4. Typical Longitudinal Grain Structure Near Trailing End of 13 mm 2090 Rod Extrusion
A. Surface  B. Center
amount of heat generated (or reducing the heat dissipated) at the die bearing surface which promotes the onset of surface tearing or incipient melting.

An examination of the extrusion microstructures after solution-heat treatment revealed a duplex structure consisting of a recrystallized layer at the surface and a fibrous, unrecrystallized core structure, as shown in Figure 4. This duplex structure was most pronounced near the tail-end of the extrusion where the recrystallized zone was thickest. At the leading end of the extrusions the depth and degree of recrystallization was much less than near the trailing end. A slight trend of increasing recrystallization with increased extrusion temperature was observed and is shown in Figure 5. This is opposite of the trend reported by Parson and Sheppard (9) for Al-Li-Mg alloys. Increased extrusion ratio also resulted in increased recrystallization as was seen by Parson and Sheppard.

An examination of as-extruded microstructures revealed a duplex structure similar to that seen after heat treatment but with some differences. The zone near the surface of the as-extruded rods appeared to consist of very fine "subgrains" with similar crystallographic orientations as evidenced by a lack of contrast when examined after a Barker's electrolytic etch. The subgrain size was also a finer size (~1-3μm) than the recrystallized grain size (~5-10μm) after solution heat treatment. The depth of the fine subgrain region in the as-extruded rod was very similar to that of the fine recrystallized grain region in solution treated rods. This would indicate that while some or all recrystallization may have occurred during subsequent heat-treatments, the final microstructure is largely determined by what occurs during the extrusion process. Additional testing, including TEM examination of the microstructures, is needed to determine the exact nature and relationship between the as-extruded subgrain structure and the recrystallized structure after heat treatment.

The results of tension tests with reduced section round specimens showed only a slight trend of decreased strength with increased extrusion temperature, as shown in Figure 6. A more significant relationship between strength and extrusion temperature had been expected based on the variation in recrystallization observed but was probably lessened due to the loss of the near-surface structure during machining of the specimens. To determine whether recrystallization reduced tension strength, full section rod specimens were tested from the head (largely unrecrystallized) and tail (substantial recrystallization) regions of additional rod extrusions. Figure 7 clearly shows lower strength in the more recrystallized tail regions as had been expected.

**Al-Li-Cu-Mg Alloys**

The effect of Mg on extrudability was examined by extruding a limited number of 2091, 8090 and 8091 billets using a 22:1 extrusion ratio. As shown in Figure 8, the Mg-containing alloys exhibited higher peak pressures than 2090 alloy at a given extrusion temperature. The low Cu content of 8090 offset most of the effect of Mg and resulted in only slightly higher peak pressure as compared to 2090. The higher total alloying levels of 8091 and 2091 resulted in progressively increasing peak pressures. An estimated extrusion limit diagram for the Mg containing alloys based on the results of the single extrusion ratio examined is given in Figure 9 where 8091 and 2091 have been combined for simplicity. The increased pressure required to extrude the Mg-containing alloys reduces the potential range of extrusion conditions as shown on the left (lower temperature limit) side of the figure. In addition, the higher total alloying content of 2091 and 8091 substantially reduces the upper temperature limit due to the onset of incipient melting and surface tearing. This was particularly evident when using the higher ram speed where no acceptable surfaces were obtained even at the lowest (~400ºC) extrusion temperature evaluated. It appeared that for 8090 alloy the surface limited conditions would be similar to those for 2090 and that overall the two alloys would extrude somewhat similarly. However, 2091 and 8091 alloys appear to have a much more limited range of acceptable extrusion conditions.
Figure 5. Effect of Extrusion Conditions on Recrystallization of 2090 Rods After Solution Heat Treatment.

Figure 6. Effect of Processing Conditions on the Yield Strength of 2090 Extrusions. (Reduced Section Specimens)

Figure 7. Effect of Processing Conditions and Specimen Location on the Yield Strength of 2090 Extrusions (Full Section Tension Specimens)

Figure 8. Effect of Alloy on Peak Extrusion Pressure.

Figure 9. Experimental Extrusion Limit Diagram

Figure 10. Effect of Processing Conditions on the Yield Strength of 8090 and 8091 Extrusions.
The 8090 and 8091 extrusion microstructures followed the same trends as did the 2090 extrusions with a duplex grain structure and a slight increase in recrystallization with increasing extrusion temperature. Differences were observed in that the 8090 and 8091 had a lower total amount of recrystallization and that both the recrystallized and, particularly, the unrecrystallized core grains were smaller than those of the 2090 extrusions.

The 8090 and 8091 extrusions also followed the same trend of decreasing strength with increasing extrusion temperature as did 2090 (see Figure 10). A limited number of notch tensile tests were conducted with 2090, 8090 and 8091. The results (see Figure 11) show that the 8XXX extrusions have a higher notch strength/yield strength ratio than the 2090 extrusions at a given yield strength. A strong inverse relationship between yield strength and the notch-yield ratio was seen for both groups. No correlation of notch-yield ratio with extrusion ratio, extrusion temperature, aging practice or specimen location was observed, other than the effect these variables had on yield strength.

A comparison was made between the extrudability of 2090 and 8090 alloys and that of conventional extrusion alloys 2024 and 6061. An extrusion ratio of 15 to 1 and a ram speed of 15-30 cm per minute were used to produce a 6 mm flat bar. The results, given in Figure 12, show 2090 and 8090 to extrude more easily than 2024 and at pressures and temperatures which approach those used for 6061.

**PRODUCTION EXPERIENCE**

Bar stock and channel extrusions have been produced from 35 cm diameter billet and an I-beam type shape (see Figure 13) from 40 cm billet. No particular difficulties were experienced in extruding these sections, and the extrudability was between that of 6061 and 2024, as had been indicated by the laboratory testing.

Aging curves developed using material from the heavy section of the I-beam shape are given in Figure 14 and show that high longitudinal yield strengths (>500 MPa) can be achieved with a range of aging conditions. When combined with Charpy impact energy, as shown in Figure 15, it can be seen that various strength-toughness combinations can be obtained depending upon the processing conditions selected.

High and low strength practices were selected for further characterization of the extrusions with the work being concentrated on the I-beam section due to its combination of heavy and thin cross-sectional areas. Good uniformity was observed down the length of the extrusions, but large variations in strength and toughness were seen due to test direction and section thickness. As shown in Figure 16, the highest combination of tension strength and Charpy impact energy was in the longitudinal (T-L) direction of the heavy section. Substantially lower strength and impact energies were obtained when the heavy sections were tested in the transverse (T-L) direction. The lighter section (web) exhibited little variation due to test direction and had yield strength-Charpy impact energy combinations intermediate to those of the thicker sections. Similar variations, although of a lesser magnitude, have been reported by Reynolds et al. (10) for Al-Li-Cu-Mg alloys. In addition to test direction and section thickness, test location affected properties which were particularly notable in the heavier sections. Differences of ~35-85 MPa were noted between the edge and center of various sections, but unlike other reports (10), the lower strength area was not always at the standard test location.

Examination of the microstructures of the various extrusion test locations indicated that grain structure and aspect ratio along with texture variations account for most of the property variations. In the case of the "I-beam" section, the heavier sections had primarily an elongated fibrous grain structure with only a small amount of recrystallization. The thinner section had a more "pancake" shaped grain structure and a higher percentage of recrystallization. The interrelationship between grain structure and aging practices and their effect on
With = Tail
Without = Head

Yield Strength -- ksi (MPa)

Figure 11. Notch Tensile Strength-Yield Strength Ratio Vs. Yield Strength.

Figure 12. Comparison of Peak Extrusion Pressures of Al-Li Alloys with Conventional Extrusion Alloys.

Figure 13. Cross-Sectional View of 2090 "I-Beam" Extrusion.

Figure 14. Aging Curves for 2090 Extrusion. (Section Thickness = 1.0"

Figure 15. Effect of Aging Practice on the Strength and Charpy Impact Energy of 2090 Extrusion.

Figure 16. Effect of Test Direction and Section Thickness on the Yield Strength and Charpy Impact Energy of a 2090 "I-Beam" Extrusion.
fracture paths and strength-toughness combinations appeared to be typical of that reported elsewhere (4,5,11-13) and will not be further discussed here.

CONCLUSIONS

1. Experimental extrusion limit diagrams for Al-Li-Cu and Al-Li-Cu-Mg alloys indicate that the addition of Mg lowers the working range by both increasing the flow stress and enhancing the onset of incipient melting and surface tearing particularly at the higher alloying levels.

2. The extrusion grain structure is influenced by the extrusion ratio and billet temperature with increased temperatures and ratios in the range examined tending to cause more recrystallization.

3. Mechanical properties are strongly influenced by recrystallization and grain shape. Elongated, unrecrystallized grains resulted in high longitudinal strength and toughness but low transverse properties. Recrystallization and "pancake" shaped grains resulted in less anisotropy but lower longitudinal strength and toughness.

4. Alloy 2090 can readily be extruded in a production environment. The extrudability of 2090 is closer to that of 6061 from the standpoint of press effort and extrusion temperatures as compared to current high strength 2XXX and 7XXX alloys.

REFERENCES