Influence of Post-Superplastic Forming Practices on the Tensile Properties of Aluminum-Lithium Alloys

S.J. Hales and H.E. Lippard

The effect of thermal processing following superplastic forming on the tensile properties of aluminum-lithium alloys is addressed. The starting materials consisted of alloys 8090, 2090, and X2095 (a Weldalite™ 049 variant) in the form of commercial-grade superplastic sheet. Experience dictates that post-forming practices aimed at a slightly underaged T6 temper produce balanced engineering properties in these alloys. The objective of this study was to assess the potential to use a T5-type temper by eliminating the solution heat treatment and/or cold water quenching steps characteristic of T6 processing. The experimental procedures adopted ensured that the tensile properties compiled were representative of the bulk material Initially, the strengthening behavior of each alloy as a function of temper selection was established. Subsequently, aging practices that resulted in peak strength and balanced properties were identified for the baseline T6 temper and two T5 tempers. The implications for replacing a T6 temper with a T5-type temper, including rapid and slow cooling following forming, are discussed on the basis of the results.

Keywords

aluminum-lithium alloys, deformation processing, heat treatment, mechanical properties, superplastic forming

1. Introduction

THE concept of built-up structures, integrated with superplastic forming (SPF) of aluminum-lithium alloys, is being evaluated for lightweight launch vehicles (Ref 1). In aerospace applications, the impetus to reduce structural weight and thus launch costs is matched by the desire to reduce manufacturing costs. The use of SPF technology to fabricate components with complex configurations has the potential to enhance the structural efficiency of cryogenic tank and dry bay assemblies (Ref 2, 3). Exploitation of the improved specific properties characteristic of aluminum-lithium alloys is also expected to translate into structural weight savings for strength- and stiffness-critical applications (Ref 4). The performance of superplastically formed components will be governed by both the SPF parameters and the post-SPF processing techniques employed.

Traditional processing of superplastically formed aluminum-lithium alloys involves placing components in the T6 temper. The T6 temper refers to the condition of material which has been "solution heat treated and artificially aged" to near-peak strength following forming operations (Ref 5). The objective of this investigation was assessment of the potential to eliminate the solution treatment and rapid cooling procedures characteristic of T6 processing. The condition of material which has been "cooled from an elevated-temperature (400 to 500 °C) shaping process and artifically aged "in the absence of an intermediate solution treatment," is referred to as a T5 temper (Ref 5).

S.J. Hales, Analytical Services and Materials, Inc., Hampton, VA 23666, USA; and **H.E. Lippard,** Department of Materials Science, Northwestern University, Evanston, IL 60208, USA

The sequence of events relevant to post-SPF T6 processing and the difference between T6 and T5 thermal processing is outlined in Fig. 1. The standard T6 procedure commences with hot removal from the SPF die and uncontrolled air cooling from forming temperatures of 480 to 540 °C. This is followed by solution heat treatment (SHT) at temperatures the same as, or higher than, the SPF temperature (T_{SPF}) and subsequent cold water quenching (CWQ). After correcting for any distortion due to the rapid cooling and an unspecified period of natural aging, artificial aging at temperatures of 130 to 190 °C imparts near-peak strength (Ref 6).

The key issues associated with temper selection are also highlighted in Fig. 1. First, reducing the number of processing operations is economically beneficial to a forming process with long cycle times (Ref 7). Second, reducing quench distortion enhances geometric reproducibility and decreases expensive rework to achieve dimensional conformance (Ref 6). Third, reducing exposure to temperatures of ≥480 °C in air during thermal processing minimizes any detrimental effect on sheet properties resulting from surface lithium depletion (Ref 8,9). However, these benefits will only be realized if it can be demonstrated that post-SPF processing modifications are not detrimental to material performance.

The compositions of the production-quality superplastic materials in the program—8090-SP, 2090-OE16, and X2095—are compared with alloy specifications in Table 1 (Ref 10). Alloy X2095 is registered with the Aluminum Association as the designation for Weldalite™ 049 alloy variants containing 3.9 to 4.6 wt% Cu (Ref 11). An example of a superplastically formed structural component evaluated in this program is shown in Fig. 2. The various elements of the partially trimmed "hat stiffener," the predominant levels of SPF true thickness strain, and the locations suitable for tensile blank extraction are indicated.

As is customary, the superplastic forming parameters used to fabricate the aluminum-lithium components were chosen on the basis of maximum biaxial formability (Ref 7). The temperatures and strain rates employed, in conjunction with the corresponding flow stresses determined in uniaxial tests, are presented in Table 2 for the three alloys. Accepted measures of part quality include geometrical reproducibility to close toler-

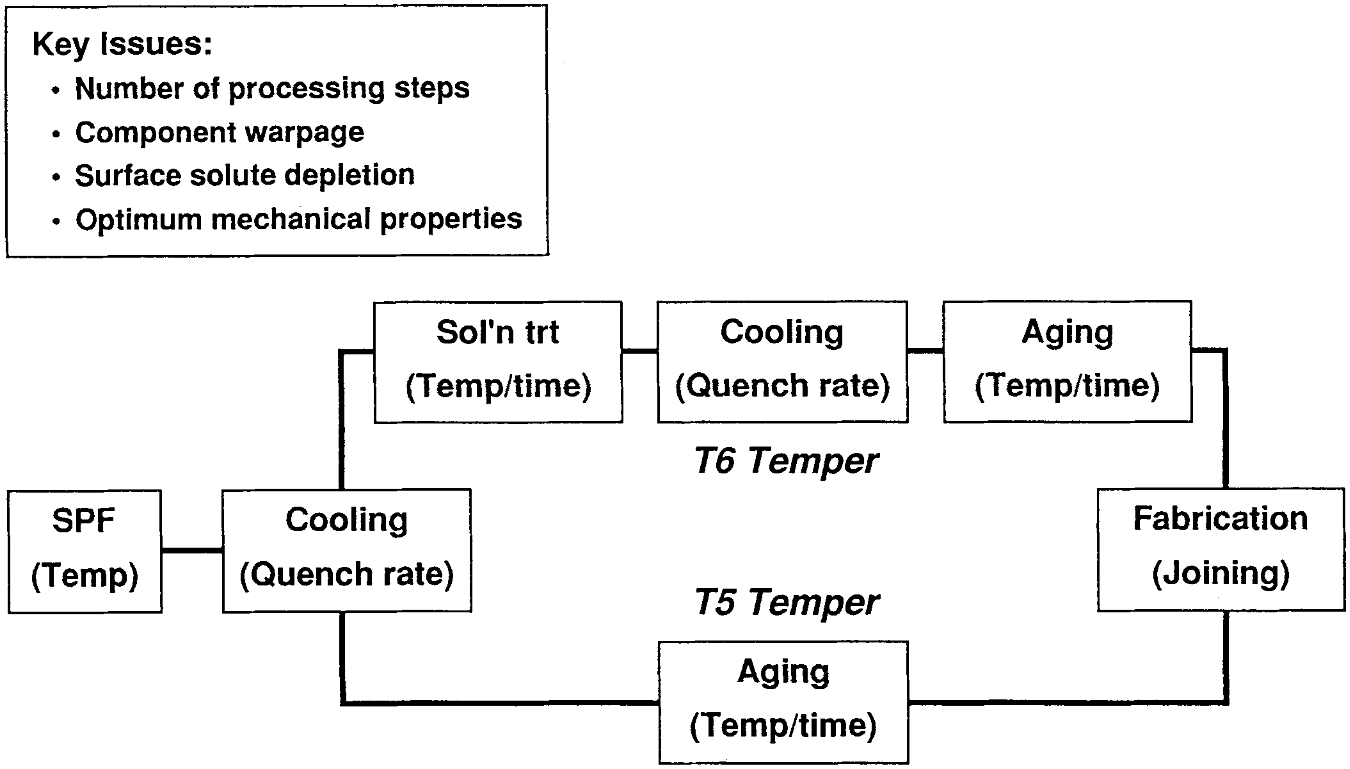

Fig. 1 A schematic illustration of the post-SPF thermal processing procedures associated with T6 and T5-type tempers. The variables characteristic of the individual steps are indicated in parentheses and the key issues associated with temper selection are also listed.

Table 1 Superplastic aluminum-lithium alloy compositions

	Composition, wt%						
Alloy	Cu	Li	Mg	Ag	Zr	Fe	Si
8090							
Specified	1.0-1.6	2.2-2.7	0.6-1.3	...	0.04-0.16	0.30 max	0.20 max
Actual	1.32	2.41	0.60	...	0.11	0.05	0.09
2090							
Specified	2.4-3.0	1.9-2.6	0.25 max	...	0.08-0.15	0.12 max	0.10 max
Actual	2.55	2.16	0.01	...	0.11	0.07	0.06
X2095							
Specified	3.9-4.6	1.0-1.6	0.25-0.8	0.25-0.6	0.08-0.16	0.15 max	0.12 max
Actual	4.43	1.22	0.39	0.39	0.13	0.07	0.05

ances and the absence of internal porosity (Ref 12). Conformance of the component to the dimensions of the superplastic forming die was ensured by the use of post-forming pressure (Ref 1). Cavitation was suppressed during superplastic forming by the application of a superimposed hydrostatic (back) pressure equivalent to 50 to 70% of the flow stress determined for each alloy (Ref 1).

A review of existing data revealed several factors important to the development of effective post-SPF processing for aluminum-lithium materials (e.g., Ref 13-20). During heat treatment of these types of alloys, the maximum attainable strength decreases with increasing aging temperature (Ref 13-15). It has been demonstrated that peak strength is also adversely affected by increasing superplastic deformation above 0.5 true strain (Ref 16-18). Material placed in a slightly underaged temper exhibits a better balance of mechanical and corrosion properties than peak-aged or overaged materials (Ref 19, 20). In commercial processing, an aging time of 8 to 40 h represents a good compromise between reproducibility of properties and heat-treating efficiency (Ref 6). It is also evident that the thickness tapering inherent to the superplastic forming process (Ref 12) and the surface solute depletion often encountered with aluminum-lithium alloys (Ref 8, 9) are potential sources of data variability.

2. Experimental Approach

The modifications to T6 processing considered included eliminating solution treatment to produce a T5/CWQ temper,

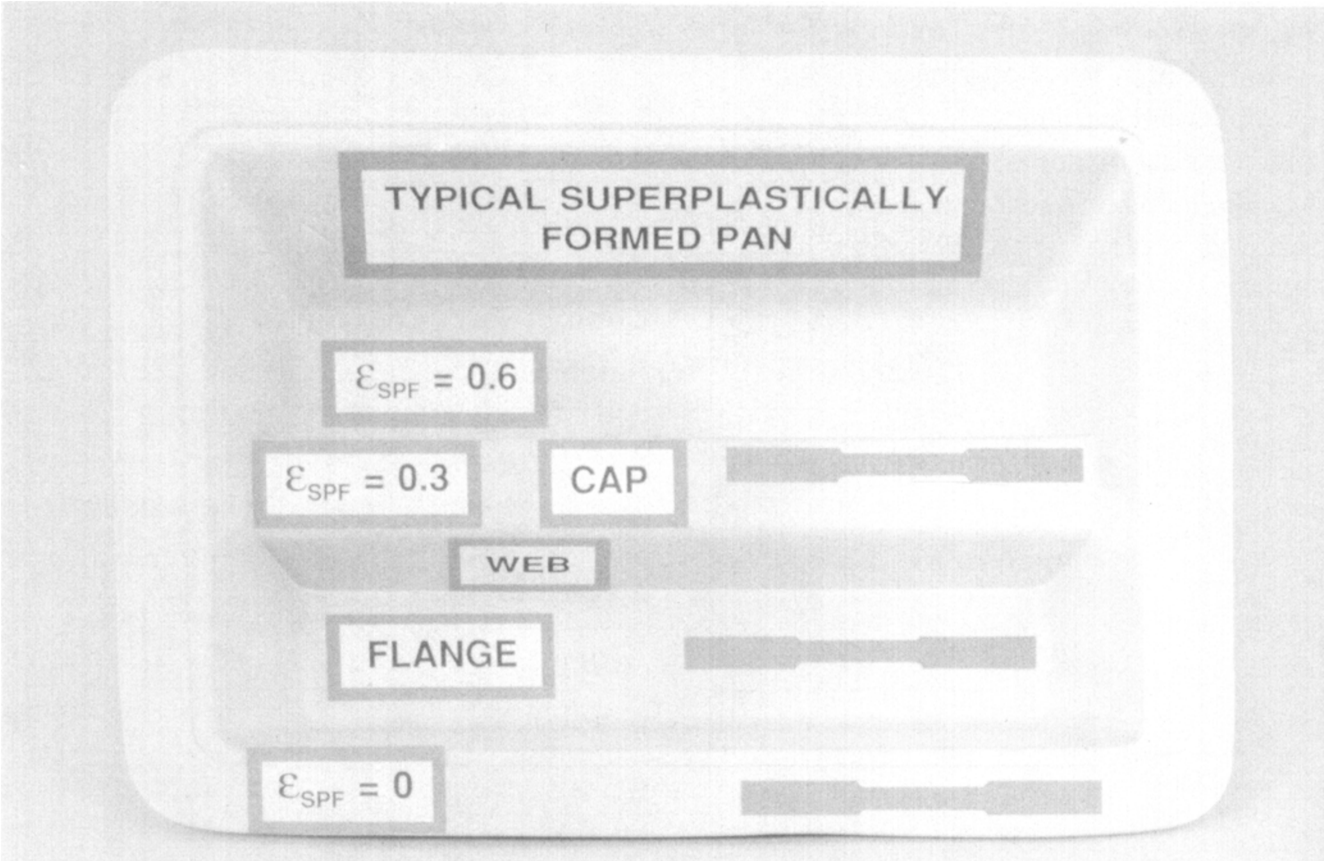

Fig. 2 One of the superplastically formed structural elements from which material for the thermal processing studies was extracted. The nominal level of superplastic strain characteristic of different regions and the location/orientation of tensile blanks are identified.

Table 2 SPF and post-SPF processing parameters

Alloy	Solution treatment temperature, °C	Superplastic forming temperature, °C	Strain rate × 10^{-4}/s	Flow stress, MPa	Back pressure, MPa
8090	530	530	2.5	3.1	2.2
2090	538	510	5.0	4.1	2.4
X2095	504	496	6.0	5.5	2.8

and eliminating solution treatment and replacing cold water quenching with accelerated air cooling (AAC) to produce a T5/AAC temper. In the latter temper, the term "accelerated" air cooling refers to the use of a fan to create moderate air movement over the hot component. Such "moving air" cooling is common practice for minimizing warpage in complex-shaped components with thin-wall sections (Ref 6). In this case, quench distortion during the T6 and T5/CWQ processing was diminished because the superplastically formed pans were self-reinforcing in the untrimmed condition. The solution treatment time was approximately 1 h at the temperatures indicated in Table 2 for the baseline T6 processing. Any effect of variation in starting condition on strengthening response was minimized by allowing the superplastically formed materials to reach a stable, naturally aged condition prior to artificial aging. For the T6 temper, a 100 h interlude is common practice for the T4 temper precursor (Ref 6). The T1 condition for T5-type processing (Ref 5) was achieved following 1000 h at ambient temperature (Ref 10).

Tensile testing represented the culmination of an extensive program addressing the effect of temper selection on the post-SPF properties of alloys 8090, 2090, and X2095 (Ref 10). The original experimental matrix incorporated three levels of superplastic strain, three aging temperatures, and eight aging times for each alloy/temper permutation. The goal of this study was to identify aging treatments of practical duration that produced balanced tensile properties in the different temper conditions. The age-hardening data compiled were used to define an experiment including only two aging temperatures (177 °C plus 163 or 191 °C) and six aging times (1 to 100 h). The size of

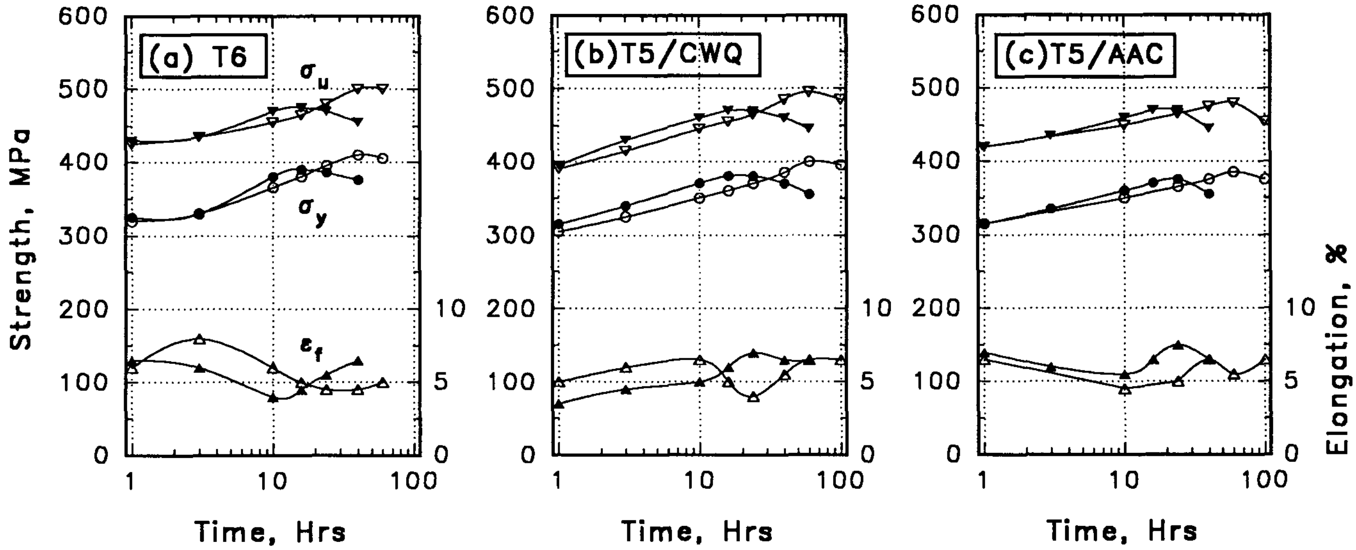

Fig. 3 The post-SPF strengthening response of alloy 8090 during artificial aging at 177 °C (open symbols) and 191 °C (closed symbols) as a function of temper/quench rate selection including: SPF + ; (a), solution treated, cold water quenched and aged; (b), cold water quenched and aged; (c), accelerated air cooled and aged.

the initial test matrix was dictated by the quantity of flat, subsize tensile specimens that could be extracted from the superplastically formed components (Fig. 2). The strengthening behavior of flat material with a thickness corresponding to a superplastic true strain of 0.6 at the gage section was evaluated. As cursory trends in the data were identified, supplementary material conditions were added to the test matrix.

The sequence for machining of specimens was designed to allow comparison of tensile properties representative of bulk material following superplastic deformation. The initial machining following extraction from the superplastically formed pans involved reducing each blank to uniform gage. The specimen thickness following this operation was controlled such that any solute-depleted layers in the areas corresponding to the gage sections were removed (Ref 10). The flat blanks were then machined to dimensions that conformed with ASTM B 557M specifications for standard subsize rectangular sheet-type specimens (Ref 21). The finished specimens were exposed to the time at temperature necessary for artificial aging only. Tensile testing was performed under crosshead displacement control with a target strain rate at yield of approximately 10^{-4}/s. Elongation was measured with back-to-back 25.4 mm gage extensometers located at the center of the 32 mm long reduced sections.

3. Results

The goal was to identify aging practices that are both commercially viable and that produce a balance of tensile properties suitable for structural applications. Each data point represents the average of at least three tensile tests; the statistical accuracy of the strength data is ±20 MPa. The elongation data are considered conservative as a result of the tendency of specimens to fail within the reduced section, but outside the specified gage length. Specifying an appropriate underaging treatment for each temper employed the following criteria:

- Minimal decrease in yield strength compared to the peak-aged properties
- Adequate ductility for an engineering material (elongation, ≥5%)
- An aging time of practical duration (8 to 40 h)

3.1 *Alloy 8090*

The post-SPF strengthening behavior of 8090 at 177 and 191 °C is shown in Fig. 3(a) for the baseline T6 processing. The aging response shows that peak aging occurs following 24 to 60 h at 177 °C or 10 to 24 h at 191 °C. Peak strength is achieved following 40 h at 177 °C or 16 h at 191 °C. The lower temperature results in higher strength, but aging at 191 °C produces better ductility in the peak strength condition. The elongation data reveal that underaging at 177 °C does not improve ductility without strength dropping below the levels achieved at the higher aging temperature. Therefore, the peak-aged condition at 191 °C best satisfies the criteria established for balanced tensile properties. In the T6 temper, $\sigma_u = 475$ MPa, $\sigma_y = 385$ MPa, and elongation = 5.5% are considered representative for post-SPF 8090 material.

The aging data pertaining to T5/CWQ processing (Fig. 3(b)) reveal that eliminating the solution treatment step has resulted in a systematic increase in the peak aging times to 40 to 100 h at 177 °C and 16 to 40 h at 191 °C. The strengthening response is such that the peak aging time has increased to 60 h at 177 °C, but remains at 16 h for aging at 191 °C. Although peak strength at the lower temperature is superior and ductility is adequate, the duration of aging exceeds the 40 h upper limit. Comparison of the elongation data suggests that the ductility will be lower following aging at the higher aging temperature. Consequently,

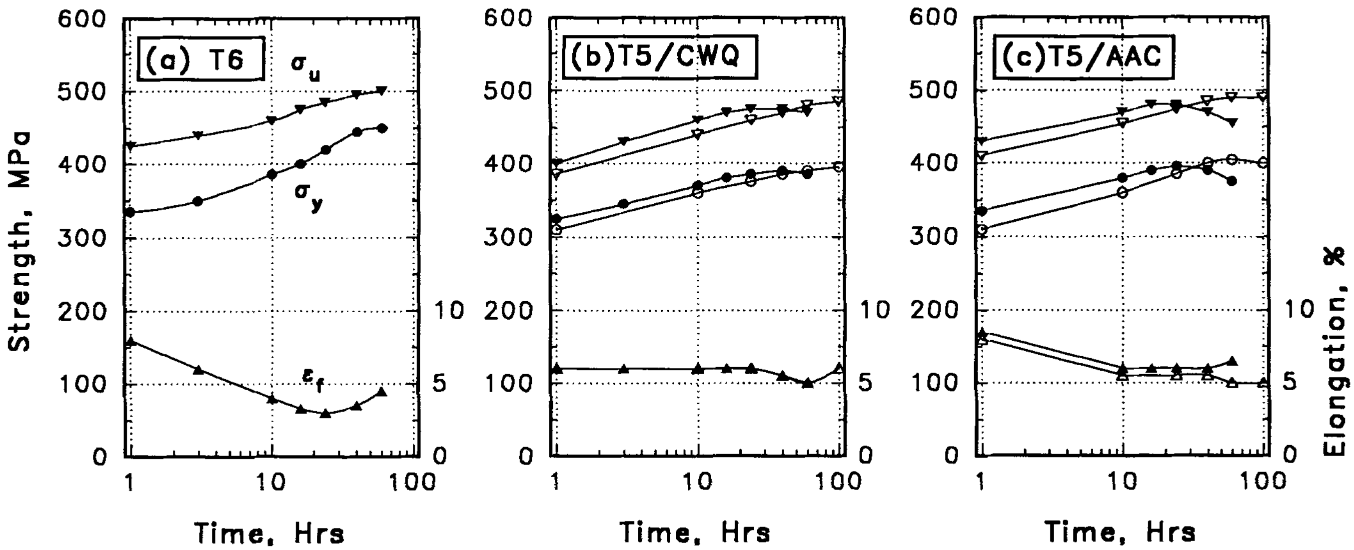

Fig. 4 The post-SPF strengthening response of alloy 2090 during artificial aging at 163 °C (open symbols) and 177 °C (closed symbols) as a function of temper/quench rate selection including: SPF + ; (a), solution treated, cold water quenched and aged; (b), cold water quenched and aged; (c), accelerated air cooled and aged.

based on the data presented, the aging treatment that produces the best balance of properties is 40 h at 177 °C. The resultant properties, which comprise σ_u = 480 MPa, σ_y = 385 MPa, and elongation = 5.5%, represent the T5 CWQ temper condition. These results show that if cold water quenching from T_{SPF} is employed, the tensile properties of alloy 8090 are basically unchanged as a consequence of eliminating solution treatment from thermal processing.

During T5/AAC processing (Fig. 3(c)), the aging behavior is very similar to that observed for the T5/CWQ temper. The data show that T5-type processing, incorporating slow cooling, has had little effect on the aging response. The peak-aged condition for strength is achieved following 60 h at 177 °C or 24 h at 191 °C. The peak-aged tensile properties are comparable for the two aging temperatures, but the aging time is too long at the lower temperature. However, aging for 40 h at 177 °C results in properties that are equivalent to the peak-aged condition following aging at 191 °C. The better ductility and the shorter aging time favors selection of 24 h at 191 C as the appropriate aging treatment. Therefore, σ_u = 470 MPa, σ_y = 375 MPa, and elongation = 7.5%, represent the properties for the T5/AAC temper in post-SPF 8090 material. The data represent a 3% drop in yield strength accompanied by an improvement in ductility compared to T6 tensile properties as a consequence of eliminating both solution treatment and cold water quenching from post-SPF processing.

3.2 *Alloy 2090*

The effect of thermal processing on the strengthening behavior of post-SPF 2090 is shown in Fig. 4. Determination of T6 properties was restricted to one aging temperature as a consequence of limited material availability. The tensile data in Fig. 4(a) reveal that the peak-aged condition is achieved after 60 h at 177 °C for T6 processing. The ductility is too low and the peak aging time too long on the basis of the criteria outlined. However, underaging for 40 h at 177°C improves ductility with only a small sacrifice in yield strength. Therefore, properties of σ_u = 495 MPa, σ_y = 430 MPa, and elongation = 5.0%, are representative of the T6 temper for post-SPF 2090 material.

The aging data pertaining to the T5/CWQ temper (Fig. 4(b)) reveal that the peak aging time has shortened to 24 to 40 h at 177 °C. The aging behavior at 163 °C reveals that the peak is located at 60 to 100 h duration. Peak strength was achieved following 24 h at 177 °C 100 h at 163 °C. Underaging for 40 h at 163 °C resulted in properties that are similar to the peak properties obtained at 177 °C. The ductility is adequate in the peak-aged condition following aging at the higher temperature, and the shorter time is beneficial. Thus, the aging treatment of choice for the T5/CWQ temper in alloy 2090 is 24 h at 177 °C, with corresponding properties of σ_u = 475 MPa, σ_y = 390 MPa, and elongation = 6.0%. These properties represent a 9% drop in yield strength and an increase in ductility.

The hardening response leading to a T5/AAC temper (Fig. 4(c)) shows that the peak location has been unaffected by the slower cooling from T_{SPF}. The peak aging times are 24 h at 177 °C and 100 h at 163 °C, with higher attainable strength at the lower aging temperature. An aging time of 100 h is too long, but underaging for 40 h at 163 °C produces tensile properties slightly higher than the peak properties following aging at 177 °C. The ductility resulting from either treatment is comparable, and both meet the criterion established. Therefore, aging for 40 h at 163 °C is specified for the T5/AAC temper. The properties associated with this treatment are σ_u = 490 MPa, σ_y = 400 MPa, and elongation = 6.0%. These properties represent a 7% drop in yield strength compared to T6 processing and a minimal change relative to the properties resulting from T5/CWQ processing.

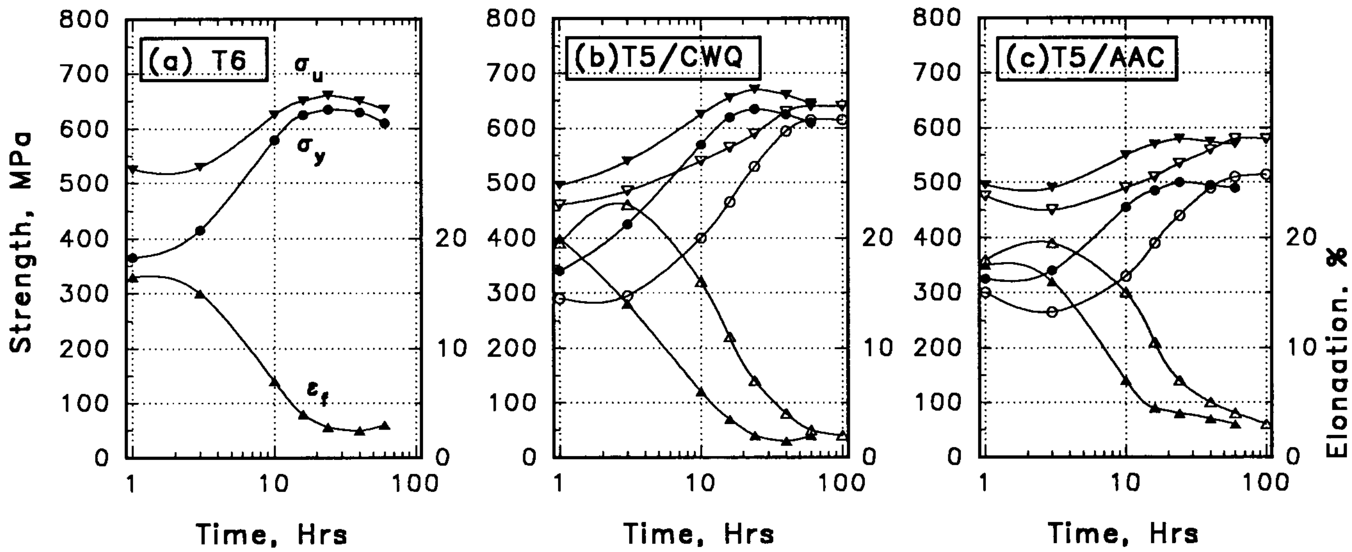

Fig. 5 The post-SPF strengthening response of alloy X2095 during artificial aging at 163 °C (open symbols) and 177 °C (closed symbols) as a function of temper/quench rate selection including: SPF + ; (a), solution treated, cold water quenched and aged; (b), cold water quenched and aged; (c), accelerated air cooled and aged.

3.3 *Alloy X2095*

The post-SPF aging behavior of alloy X2095, documented in Fig. 5, is different from that reported for alloys 8090 and 2090. Common to all three thermal processing practices, the alloy exhibits a reversion in properties from the naturally aged condition. It is evident that the behavior occurs during short-term artificial aging and varies in size and duration with aging temperature. The aging data related to T6 processing show that the properties drop by at least 20% and only return to that of the naturally aged condition after 3 h at 177 °C. The aging data pertaining to the T5-type tempers (Fig. 5(b) and (c)) show that the duration of the reversion is similar. During T5/CWQ and T5/AAC processing, the properties only return to that of the naturally aged condition after 16 to 24 h at 163 °C and 3 to 10 h at 177 °C. The aging response also shows that the depth of the reversion is influenced by aging temperature. For both T5 procedures, the drop in properties during aging at 163 °C is approximately twice that observed at 177 °C. This aging response is comparable to the behavior exhibited by other Weldalite™ 049 alloys with similar composition (Ref 27).

The strengthening behavior leading to the T6 temper (Fig. 5(a) indicates that the peak aging time is 16 h at 177 °C. Again, limited availability of material restricted determination of X2095-T6 tensile properties to a single aging temperature. The peak-aged ductility is low, but the trend in the elongation data suggests that satisfactory improvement can be attained via underaging. The reversion behavior documented in the aging data results in exceptional tensile ductility in the highly underaged condition. Examination of the data shows that aging for 10 h does not result in a large decrease in strength, but the ductility is less than 5%. In contrast, an aging time of 3 h produces the required ductility, but with too great a sacrifice in strength compared to the peak-aged values. The trend suggests that the best balance between strength and ductility can be attained by specifying an underaging time of approximately 8 h. However, restricted to the actual data compiled, an aging treatment of 10 h at 177 °C constitutes the best choice for achieving a balance of tensile properties. Therefore, properties of σ_u = 635 MPa, σ_y = 600 MPa, and elongation = 4.0%, are the closest representation of the slightly underaged T6 temper condition.

The strengthening response leading to a T5/CWQ temper (Fig. 5(b)) reveals that peak aging of alloy X2095 is achieved following 60 h at 163 °C and 24 h at 177 °C. In contrast to the general trend in the tensile data compiled, peak strengths are higher as a result of aging at the higher temperature. The properties are also superior to the peak-aged T6 properties; the reason for this anomalous behavior is uncertain. The elongation in this high-strength condition is inadequate and an underaging treatment is necessary. Interpolation from the data suggests that 8 to 10 h at 177 °C will result in adequate ductility. However, aging for 24 h at 163 °C is the best choice for achieving balanced properties, on the basis of the data compiled. The corresponding T5/CWQ properties are σ_u = 570 MPa, σ_y = 510 MPa, and elongation = 4.0%. The underaged yield strength documented for the T5/CWQ temper represents an approximately 15% decrease compared to the underaged T6 properties shown.

The data for the T5/AAC temper in Fig. 5(c) show that the strengthening response is very similar to that documented for the T5/CWQ temper. The aging times for peak properties are the same for both aging temperatures—namely, 60 h at 163 °C or 24 h at 177°C. Consistent with most of the data compiled, the maximum attainable strength is higher at the lower aging temperature. Selection of an underaging treatment of 40 h at 163 °C or 16 h at 177 °C produces a better balance of properties. Again, aging at the lower temperature produces a higher strength for a given level of ductility. Therefore, the T5/ACC properties for alloy X2095 comprise σ_u = 560 MPa, σ_y = 490 MPa, and elongation = 5.0%. These results represent an approximately 18%

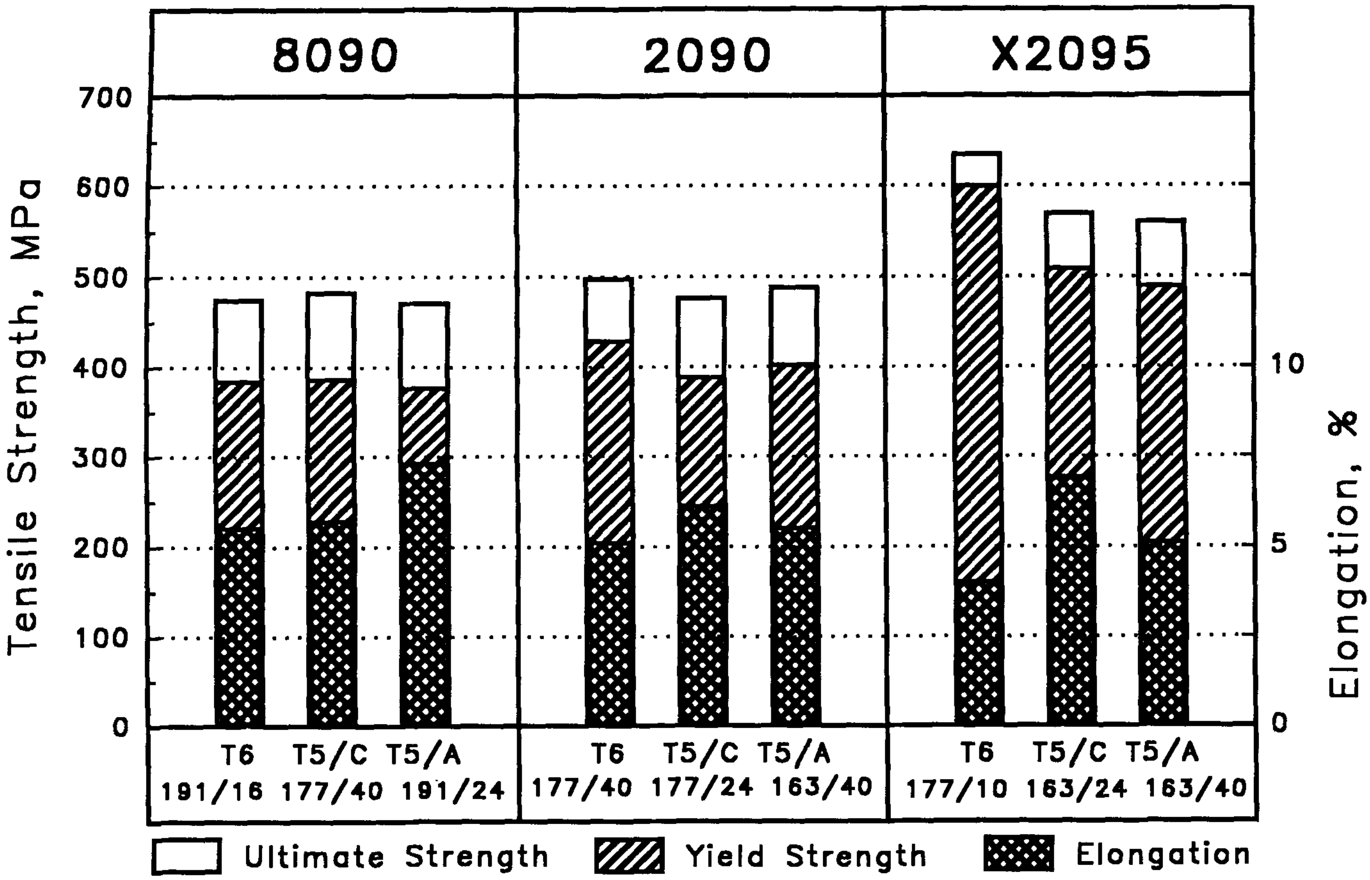

Fig. 6 Summary of the impact of thermal processing on the post-SPF properties of alloys 8090, 2090, and X2095. The selection criterion for aging treatments was maximum yield strength with adequate ductility (≥5%) in a practical aging time (≤40 h).

drop in yield strength in comparison to the T6 properties selected.

4. Discussion

Recommendation concerning the use of T5-type tempers must necessarily include consideration of the superplastic forming parameters employed. The temperature differential between T_{SPF} and T_{SHT} for each alloy may influence the strengthening response during subsequent artificial aging. Specifically, the difference in temperature will govern the effectiveness of thermal exposure during superplastic forming to substitute for a formal heat solution treatment. Traditionally, T_{SHT} is selected to maximize the amount of solute put into solution in the absence of incipient melting (Ref 22). Variation in solute content as a result of a lower T_{SHT} will also affect the quench sensitivity of the post-SPF materials during T5 processing. The optimum cooling rate usually represents a compromise between retaining the supersaturated solid solution and minimizing residual stresses (Ref 22). The extent to which post-SPF processing can be simplified without sacrificing tensile properties is illustrated in Fig. 6. For the purposes of discussion, a decrease in yield strength of ≤5% was the criterion adopted for assessing the potential to replace a T6 with T5-type temper (Ref 10).

The results for alloy 8090 show that tensile properties are unaffected by eliminating solution treatment or employing accelerated air cooling during post-SPF thermal processing. The lack of difference between T6 and T5/CWQ can be attributed to the absence of a temperature differential between T_{SHT} and T_{SPF}, as shown in Table 2. The data imply that the alloy is in a fully solution-treated condition at the conclusion of forming and does not require subsequent solution treatment. Further, the small change resulting from eliminating cold water quenching for the T5/AAC temper indicates that rapid cooling is also not required for post-SPF property retention. A lack of quench sensitivity has been cited previously as one of the advantages associated with the use of alloy 8090-SP (Ref 23). Both the T6 and T5 properties documented are consistent with the behavior reported for production-quality 8090 material (Ref 8, 24).

The post-SPF data for alloy 2090 show that the tensile properties are influenced more by removal of the solution treatment step than using a slower quench rate for a T5-type temper. The T6 properties presented compare favorably with other data for 2090-OE16 superplastic material (Ref 14). Upon replacing T6 with T5/CWQ processing, the yield strength is degraded beyond the prescribed 5% margin and is accompanied by a reduction in the peak aging time. It is suggested that both observations are a consequence of the large temperature differential between T_{SPF} and T_{SHT} for alloy 2090, as presented in Table 2. The data indicate that the material is too far from a solution-treated condition at the conclusion of forming for the subsequent aging behavior to remain unaffected. The resultant decrease in the amount of solute available for strengthening explains both the drop in peak strength and the shorter peak aging time (Ref 22).

Rationalization of the similarity in properties between the two T5-type tempers is difficult based on the data compiled. It has been documented that alloy 2090 is quench sensitive (Ref 25), but the large temperature differential between T_{SHT} and T_{SPF} makes the effect of the slower cooling rate uncertain. The implication of the data presented is that solution treatment cannot be removed without excessive degradation in T6 properties at the particular T_{SPF} employed. However, increasing the forming temperature, such that $T_{SPF} \sim T_{SHT}$ would increase the potential for the material to approach a fully solution-treated condition at the conclusion of forming. It is anticipated that T5/CWQ properties much closer to T6 properties would result, assuming adequate superplastic formability at the higher forming temperature. Uniaxial superplastic elongations in excess of 500% have been attained in superplastic 2090 in the temperature range of 530 to 546 °C without back pressure (Ref 13, 14, 26).

The X2095 data suggest that the superplastically formed material is affected more by replacing T6 with T5/CWQ processing than the 8090 or 2090 alloys. However, the data presented in Fig. 6 are somewhat misleading because the ductility in the baseline T6 condition does not meet the criterion established (elongation ≥5%). The effect of eliminating solution treatment from thermal processing on post-SPF yield strength may be exaggerated as a consequence. By interpolation from the data compiled in Fig. 5(a), an underaging treatment of 8 h at 177 °C would yield properties of $\sigma_u = 600$ MPa, $\sigma_y \sim 525$ MPa, and elongation ~5%. Acceptable ductility has been obtained by specifying an equivalent underaged condition in conventionally processed Weldalite™ 049 material of similar composition (Ref 27). These properties constitute a better representation of the T6 baseline for the purpose of assessing the influence of thermal processing on post-SPF properties. Consequently, the T5/CWQ properties represent only a 3% decrease in yield strength, rather than the 15% drop that was apparent prior to interpolation. Similarly, comparison of the interpolated T6 properties with the T5/AAC properties presented in Fig. 6 reveals only a 7% drop in yield strength, as opposed to 18%.

These latter results imply that solution heat treatment can be eliminated from post-SPF processing of alloy X2095 at the forming temperature employed. The T5/CWQ data suggest that the material approximates a solution-treated condition at the conclusion of forming and, as seen in Table 2, the temperature differential between T_{SPF} and T_{SHT} for alloy X2095 is relatively small. However, replacing cold water quenching with accelerated air cooling appears to result in excessive degradation of tensile properties. The T5/AAC data suggest that the material is sensitive to cooling rate, which is plausible considering the composition of alloy X2095 (Table 1). It has been demonstrated that increasing the copper content of alloy 8090 results in increased quench sensitivity (Ref 8). The data reported are consistent with behavior documented for superplastic Weldalite™ 049 following similar post-SPF thermal processing modifications (Ref 18).

It may still be feasible to use a cooling rate intermediate between cold water quenching and accelerated air cooling for a T5 temper, while retaining the forming temperature. The implementation of aqueous glycol quenching, for example, would permit the cooling rate to be moderated in a controlled manner. It has been demonstrated that residual stresses can be greatly reduced in sheet materials of thicknesses similar to those characteristic of SPF components (Ref 28). Such an approach is common industrial practice for controlling quench distortion while still retaining target properties in non-lithium bearing aluminum alloys. Another possibility, similar to the case of alloy 2090, may be to increase T_{SPF} so that the potential to employ slower cooling rates increases. It has been demonstrated that uniaxial elongations of greater than 600% are attainable in superplastic X2095, while forming between 504 to 516 °C in the absence of back pressure (Ref 15, 18).

Comparison of post-SPF properties from different sources must account for the influence of superplastic strain. The tensile data compiled are characteristic of aluminum-lithium materials superplastically deformed to a true thickness strain of 0.6. Another pertinent aspect of this investigation was the focus on compiling tensile data that were representative of the bulk material. Precautions included suppressing cavitation during superplastic forming and accounting for thickness tapering, lithium depletion, and quench distortion during specimen preparation (Ref 8, 9). The care taken during specimen machining served to minimize scatter in the strength data, but the ductility data were conservative because of fracture location. It is recognized that any assessment of the potential use of T5-type tempers must also address the effect of thermal processing on all properties relevant to engineering applications. Although not evaluated in this study, it has been demonstrated that incomplete solution heat treatment and/or the use of slower cooling rates can adversely affect the fracture toughness and corrosion resistance of aluminum-lithium alloy materials (Ref 19, 20).

In the event that cost-effective implementation of superplastic forming technology demands simplified post-SPF processing, an important issue emerges from this study. The superplastic forming temperature employed may govern the successful application of T5-type tempers to aluminum-lithium alloys. Conventional wisdom dictates that selection of superplastic forming parameters on the basis of optimum superplastic response, independent of the maximum strain required, promotes geometrical conformance and minimizes cavitation (Ref 7, 12). The tensile properties reported here reflect the use of superplastic forming temperatures that produced the best superplastic response in the individual materials ($T_{SPF} \leq T_{SHT}$). However, the maximum superplastic strain typically required for complete formation of structural components is relatively low compared to the uniaxial strain-to-failure common to superplastic materials. The broad range of temperatures over which these alloys exhibit a superplastic response may create some flexibility in forming parameter selection. A component is least likely to require a formal solution treatment subsequent to forming operations if $T_{SPF} \geq T_{SHT}$. Therefore, the most appropriate superplastic forming temperature may not be that at which maximum formability is attained per se, but rather the highest temperature at which formability is adequate to fulfill a particular component geometry.

5. Conclusions

The post-SPF properties of the aluminum-lithium alloys 8090, 2090, and X2095 were evaluated as a function of thermal processing. The tensile data compiled were representative of material superplastically deformed to 0.6 true strain. The results reveal the extent to which post-SPF procedures can be simplified without sacrificing T6 properties.

For alloy 8090-SP, replacing the T6 temper with either the T5/CWQ or T5/AAC condition is a viable option for post-SPF processing. The data show that both solution treatment and rapid cooling can be eliminated with a ≤5% drop in tensile yield strength at the forming temperature employed.

For alloy 2090-OE16, the data reveal that solution treatment cannot be eliminated without excessive degradation of post-SPF T6 properties. The large temperature differential between T_{SHT} and the T_{SPF} employed was considered responsible, but the use of a higher forming temperature may permit T5 processing to be implemented.

For alloy X2095, solution treatment does not appear necessary, but replacing cold water quenching with accelerated air cooling resulted in a ≥5% drop in yield strength for a T5 temper. The selection of a higher superplastic forming temperature may increase the potential to adopt a T5/AAC temper.

Acknowledgments

This work was conducted in support of the National Launch System Program in the Materials Division at NASA Langley Research Center, Hampton, VA 23681-0001. The research was funded by the National Aeronautics and Space Administration under Contract No. NAS1-19399, with Mr. Thomas T. Bales as technical monitor. Henry E. Lippard gratefully acknowledges the support of the Langley Aerospace Research Summer Scholar program during 1990, 1991, and 1992.

References

1. S.J. Hales, T.T. Bales, W.F. James, and J.M. Shinn, Fabrication of Structural Components from Commercial Aluminum Alloys Using Superplastic Forming, *Superplasticity in Aerospace II*, T.R. McNelley and H.C. Heikkenen, Ed., TMS, 1990, p 167-185
2. R.C. Davis, D.M. Royster, and T.T. Bales, Superplastically Formed Titanium Hat-Stiffened Panels, NASA Tech. Briefs, Vol 14 (No. 1), 1990, p 63-64
3. S.J. Hales and J.A. Wagner, Superplastic Forming of Al-Li Alloys for Lightweight, Low-Cost Structures, *Technology 2000*, NASA Conf. Publ. 3109, Vol 2, 1991, p 200-209
4. R.J. Rioja and R.H. Graham, Al-Li Alloys Find Their Niche, *J. Adv. Mater. Process.*, Vol 142 (No. 6), 1992, p 23-26
5. Metallurgy of Heat Treatment and General Principles of Precipitation Hardening, *Aluminum: Properties and Physical Metallurgy*, J.E Hatch, Ed., American Society for Metals, 1984, p 134-177
6. D.S. Thompson, O.R. Singleton, R.D. McGowan, and G.E. Spangler, Heat-Treatable Aluminium Alloys and Heat-Treating Techniques, *J. Sci. Ind. Res.*, Vol 29 (No. 5), 1970, p 219-231
7. D. Stephen, Designing for Superplastic Alloys, *Superplasticity*, NATO/AGARD-LS-168, SPS Ltd., Loughton, Essex, England, 1989, p 7.1-7.37
8. A.J. Shakesheff, D.S. McDarmaid, and P.J. Gregson, Effect of Microstructure on Tensile and Fatigue Properties of Superplastically Formed Al-Li-Cu-Mg-Zr 8090 Alloy Sheet, *J. Mater. Sci. Technol.*, Vol 7 (No. 3), 1991, p 276-281
9. J.M. Papazian, G.G. Bott, and P. Shaw, Effects of Lithium Loss on Strength and Formability of Aluminum-Lithium Alloys 8090 and 2090, *Mater. Sci. Eng.*, Vol 94 (No. 2), 1987, p 219-224
10. S.J. Hales and H.E. Lippard, "Effect of Thermal Processing Practices on the Properties of Superplastic Al-Li Alloys," NASA Contractor Report No. ?, 1993
11. *Registration Record of ... Designations and Chemical Composition Limits for Wrought ... Aluminum Alloys*, Aluminum Association, Feb 1991
12. C.H. Hamilton, Superplastic Sheet Forming, *Superplasticity*, NATO/AGARD-LS-168, SPS Ltd., Loughton, Essex, England, 1989, p 2.1-2.23
13. T. Tsuzuki and A. Takahashi, Superplastic Forming Under Hydrostatic Pressure and Heat Treatments in an Al-Li Alloy, *J. Jpn. Inst. Light Metals*, Vol 39 (No. 11), 1989, p 824-830
14. C.C. Bampton, B.A. Cheney, A. Cho, A.K. Ghosh, and C. Gandhi, Superplastic Forming of Aluminum-Lithium Alloy 2090-OE16, *Superplasticity in Aerospace*, H.C. Heikkenen and T.R. McNelley, Ed., TMS-AIME, 1988, p 247-259
15. B.-T. Ma and J.R. Pickens, "Superplastic Formability of Al-Cu-Li Alloy Weldalite™049," NASA Contractor Report 4367, Martin Marietta Laboratories, May 1991
16. D.S. McDarmaid and A.J. Shakesheff, The Effect of Superplastic Deformation on the Tensile and Fatigue Properties of Al-Li (8090) Alloy, *Proc. 4th Int. Al-Li Conf.*, G. Champier, B. Dubost, D. Mianney, and L. Sabetay, Ed., *J. Phys. (Orsay)*, Vol 48 (No. 9), C3, 1987, p 257-268
17. M.J. Reynolds, C.A. Henshall, and J. Wadsworth, Superplastic Forming Characteristics and Properties of Aluminum-Lithium Sheet Alloys, *Aluminum-Lithium Alloys: Design, Development and Application Update*, R.J. Kar, S.P. Agrawal, and W.E. Quist, Ed., ASM International, 1988, p 357-399
18. P.J. Smith-Hartley, K.S. Kumar, and S.A. Brown, The Effects of Processing Parameters on the Post-SPF Microstructure and Mechanical Properties of Weldalite™ 049, *Advances in Superplasticity and Superplastic Forming*, N. Chandra, R.E. Goforth, and H. Germestani, Ed., TMS, 1993
19. W.E. Quist and G.H. Narayanan, Aluminum-Lithium Alloys, *Aluminum Alloys—Contemporary Research and Applications*, A.K. Vasudevan and R.D. Doherty, Ed., Treatise on Materials Science and Technology, Vol 31, Academic Press, 1989, p 219-254
20. R.C. Dorward, On the Mechanical Properties and Stress Corrosion Resistance of Ternary Al-Cu-Li and Quaternary Al-Li-Cu-Mg Alloys, *Mater. Sci. Eng.*, Vol 84, 1986, p 89-95
21. "Standard Methods of Tension Testing Wrought and Cast Aluminum- and Magnesium-Alloy Products," *Annual Book of ASTM Standards*, Vol 03.01, ASTM, 1988, p 52-62
22. E.A. Starke and W.E. Quist, The Microstructure and Properties of Aluminum-Lithium Alloys, *New Light Alloys*, NATO/AGARD-LS-174, SPS, Ltd., Loughton, Essex, England, 1990, p 2.1-2.21
23. W.S. Miller and J. White, The Development of Superplastic 8090 and 8091 Sheet, *Superplasticity in Aerospace*, H.C. Heikkenen and T.R. McNelley, Ed., TMS-AIME, 1988, p 211-228
24. B.J. Dunwoody and R.J. Stracey, Superplastic Forming of Aluminum Alloys, *J. Met. Mater.*, Vol 5 (No. 8), 1989, p 464-467
25. M.E. Donnellan and W.E. Frazier, An Examination of the Quench Sensitivity of Alloy 2090, *Aluminum-Lithium Alloys V*, Vol 1, T.H. Sanders and E.A. Starke, Ed., MCEP Ltd., Birmingham, England, 1989, p 355-364

26. C.W. Cho, B.A. Cheney, D.J. Lege, and J.I. Petit, Superplasticity of 2090 Sheet at Hot Rolled Gauge, *Proc. 4th Int. Al-Li Conf.*, G. Champier, B. Dubost, D. Mianney, and L. Sabetay, Ed., *J. Phys. (Orsay)*, Vol 48 (No. 9), C3, 1987, p 277-283
27. J.R. Pickens, F.H. Heubaum, T.J. Langan, and L.S. Kramer, Al-(4.5-6.3)Cu-1.3Li-0.4Ag-0.4Mg-0.14Zr Alloy Weldalite™ 049, *Aluminum-Lithium Alloys V*, Vol 3, T.H. Sanders and E.A. Starke, Ed., MCEP Ltd., Birmingham, England, 1989, p 1397-1414
28. O.R. Singleton, An Analysis of New Quenchants for Aluminum, *J. Met.*, Vol 20 (No. 11), 1968, p 60-67