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IMPROVED PERFORMANCE IN Al-Mg-Si (6XXX) EXTRUDED, STRUCTURAL ALLOYS THROUGH MICROSTRUCTURAL CONTROL

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Abstract

The age hardening Al-Mg-Si (6XXX) alloys in extruded form are currently under consideration for automotive structural applications, where the in-service conditions require a demanding combination of properties. In the present work, the properties (strength, toughness, formability, "deformability" and thermal stability) of extruded 6XXX alloy sections have been assessed, and these properties related to the microstructure of the extrusions. Specifically, the effects of alloy composition and final ageing conditions (temper) on microstructure and properties have been evaluated. Most significantly, it has been shown that extrusions in overaged tempers possess a good combination of properties for structural applications, namely: adequate strength and formability, high levels of toughness, good thermal stability and a high resistance to "splitting" (fracture) during crush deformation. Also, advantages realised through the use of overaged tempers appear to be related to the actual tensile properties and not the inherent strength of the alloy, as determined by the levels of the major alloying additions Mg and Si.

Introduction

The demand for more lightweight, fuel efficient and enhanced performance automobiles has led automotive manufacturers to consider aluminium as an alternative to steel for structural and body panel applications. The approaches to automotive design using aluminium include pressed sheet structures made by the Aluminum Vehicle Technology (AVT) route developed by Alcan [1], which is being applied currently in the Aluminum Intensive Vehicle (AIV) programme of Ford, and the use of aluminium extruded sections and nodal castings, the so-called "Spaceframe" structures, as applied currently in the Audi A8 [2]. Both of these approaches use aluminium body panels which may be joined by a number of methods to the underlying aluminium structure. In addition to these "whole body structures", however, there is also great potential for the application of Al-Mg-Si (6XXX) alloy extruded sections in other structural components, such as door intrusion beams and bumper reinforcements, and as decorative or "bolt-on" parts. Also, it is likely that the automotive designs utilizing sheet aluminium monocoque structures will also use extrusions (and castings) to produce "hybrid" structures; thus, there is a clear need to understand the structural performance of extrusions for automotive applications.

The specific application dictates, to some extent, the strength required of an extruded section, although design features such as section shape (cross section) and gauge (thickness) may be used to meet the in-service strength requirements of any given component. Strength may be varied through: (a) alloy composition, the level of Mg_2Si, and excess Si and Cu additions being the major contributors, (b) extrusion processing conditions, and (c) final ageing (temper). A guide to the strength levels attainable in some of the more common 6XXX alloys is given in the compositional plot of Figure 1, in which strength contours are plotted for alloys in a peak aged (T6) condition. It should be remembered that additions of Cu, as in AA6061 alloys, will also contribute to strength.

Of the extrusion processing conditions known to affect strength, extrusion exit temperature and quench rate are, perhaps, the most significant. Following extrusion, these alloys develop their strength through a precipitation hardening effect in which ß"-Mg_2Si, or a Cu-containing derivative if Cu is present in the alloy in sufficient quantity, precipitates from a supersaturated α-Al solid solution, although grain size and structure may contribute also, but to a lesser extent. Thus, the final ageing temperature, and time at temperature, are important factors in determining the level of strength attainable.

A further major requirement for automotive applications is relatively high formability, as the extrusions are unlikely to be used in the as-extruded (straight) condition, but are likely to be bent or twisted. The highest formability is present in the as-extruded (T4) condition, which represents the lowest level of strength; thus, to realise the strength potential of the alloy, some ageing is required. In practice, this may be applied either through a formal ageing treatment or through the adhesive cure and/or paint bake cycles, which may range in temperature from ~150°C to 200°C for times of up to 1 hour, and which are applied during vehicle manufacture.

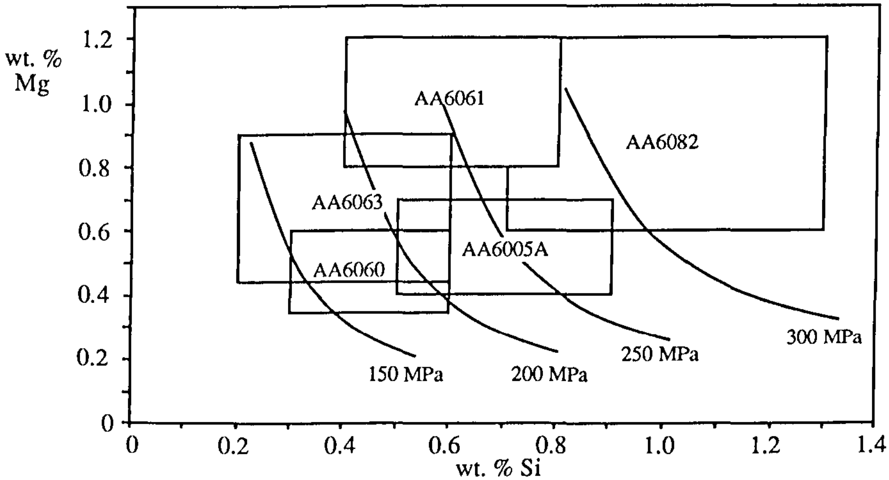


Figure 1 - The compositional limits of some common 6XXX alloys, together with contours representing typical yield stress levels attainable in the peak aged (T6) condition.

Other important properties of the extrusions are toughness and "deformability", which may or may not be a single property, thermal stability and, in some cases, corrosion and fatigue resistance, which are beyond the scope of this paper. For structural applications, the inherent "toughness" of the extrusions, however measured, should be as high as possible for a given level of strength. In this respect, the influence of some aspects of alloy composition and extrusion processing conditions on toughness is described elsewhere [3,4]. In addition, the ability to join the extrusions, either to sheet structures, to other extrusions or to cast nodes is another important requirement, but is also beyond the scope of this paper, and will not be discussed further. Once in-service, the extrusions should respond in a predictable manner to impact or crush deformation, and should be thermally stable throughout the lifetime of the car.

The major objective of this paper is to describe some work carried out within Alcan International Limited concerning the relationships between these various properties of 6XXX alloy extruded sections. Various 6XXX alloys have been extruded on a production press into hollow sections and, following ageing to different tempers, their properties have been assessed. In the present work, data from three alloys, which represent a wide strength range, are presented; these are typical AA6063, AA6005A and AA6082 compositions (see Figure 1).

Experimental

Specimens taken from lengths of extruded sections of the different alloys have been evaluated in the as-extruded (T4) condition, and following ageing, including underageing (1 and 2 hours at 180°C (UA)), peak ageing (6 hours at 180°C (T6)), and overageing (8 hours at 210°C (T8)). Tensile testing in the L orientation, and Kahn tear testing in the L-T orientation have been carried out using standard test specimens. Also, the thermal stability of the extrusions in the different tempers has been assessed following "exposure" for 1 month at 80°C, a time/temperature regime designed as an accelerated, in-service test; following this exposure, mechanical properties have been re-assessed.

The formability of the extrusions has been assessed from tensile elongation to failure data, and from simple r/t bend tests, where r is the radius of the bend and t is the section thickness, on specimens taken from the hollow sections. Also, measurements of "springback" have been made on 3 mm thick specimens following 90° press bends about a 5 mm internal radius.

The "deformability" of the extrusions has been evaluated using a longitudinal crush test applied to a single-cell, hollow section (which measured approximately 100 mm x 70 mm, with corner radii and a wall thickness of 3 mm), in which the collapse performance in the presence of a V-notch "trigger indent" has been studied. In this test, the average crush force is measured over a set displacement of 200 mm, and an assessment made of the propensity to "splitting" (fracture) of the different alloys/tempers.

Results and Discussion

The effects of the different ageing practices on the strength of the AA6063, AA6005A and AA6082 alloys are shown in Figure 2. From this figure, it can be seen that the strength range of the alloys under study varies widely, with the 0.2% proof (yield) stress ranging from ~90 MPa in the AA6063 alloy in the T4 temper to ~310 MPa for AA6082 in the T6 temper. It should be noted that the ageing kinetics of the alloys are different in that rapid strengthening occurs in the AA6005A and AA6082 alloys, whereas the ageing response of the more dilute AA6063 alloy is less marked; however, maximum strength is achieved in all alloys following ageing for 6 hours at 180°C. Also, the extent to which the alloys are overaged by the application of 8 hours at 210°C is variable.

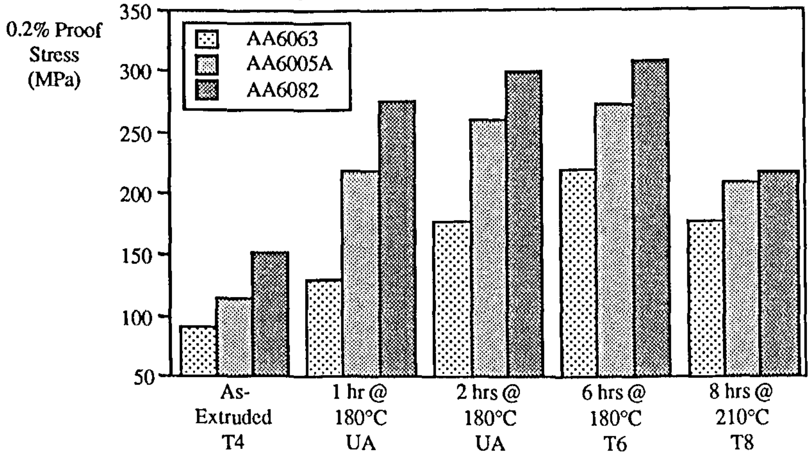


Figure 2 - The effect of temper on the 0.2% Proof Stress of 6XXX alloy extrusions.

The results of the Kahn tear test show that the alloys behave differently in terms of the effect of ageing to peak strength on "toughness", as shown in Figure 3(a and b). In the case of the AA6063 alloy, both the Unit Initiation Energy (U.I.E.) and Unit Propagation Energy (U.P.E.) values decrease with ageing time until the T6 condition is reached, whereas for the AA6005A and AA6082 alloys, the U.I.E. and U.P.E. values reach a minimum after approximately 2 hours at 180°C, and remains almost constant with continued ageing up to the T6 condition. These data are consistent with the proof stress data presented in Figure 2, in which the rapid ageing response of the more solute-rich AA6005A and AA6082 alloys leads to relatively high levels of strength, and the concomitant reduced levels of "toughness", being achieved after comparatively short ageing times. However, continued ageing (overageing - T8 temper) from that of the T6 condition results in a significant increase in both the U.I.E. and U.P.E. values for all alloys. Also, the intermediate strength AA6005A alloy gives the highest values of U.P.E. for all tempers (see Figure 3).

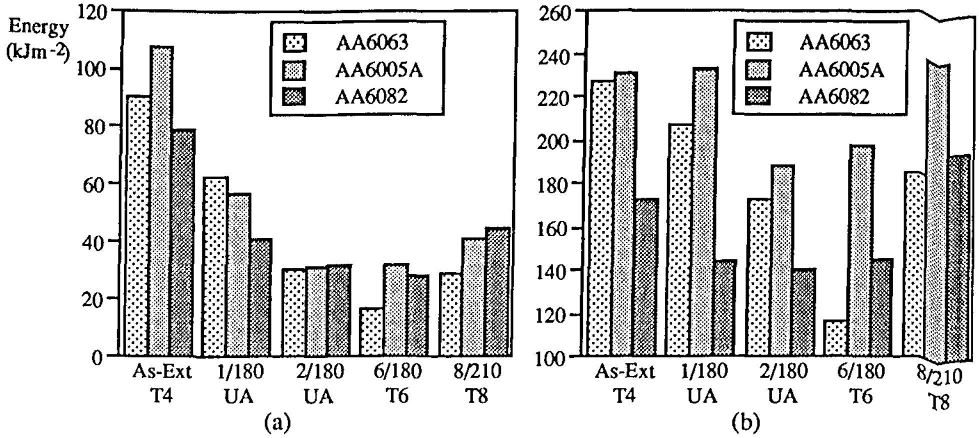
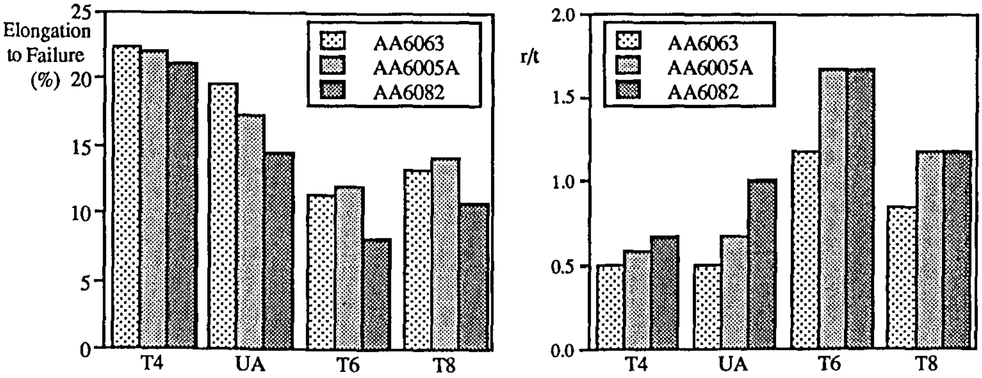


Figure 3 - The effects of temper on the Kahn tear: (a) Unit Initiation Energy (U.I.E.), and (b) Unit Propagation Energy (U.P.E.) of 6XXX alloy extrusions.

From the tensile and Kahn tear "toughness" data alone, it is not possible to select the optimum alloy/temper combination for automotive, structural applications, as these data give little information regarding the formability of the extrusions and their "deformability" once in-service. Also, it should be recalled that component design can, to a large extent, be used to overcome the deficiencies of a given alloy/temper, at least as far as strength requirements are concerned. A guide to the formability of the alloys in the different tempers may be inferred from tensile elongation to failure data in which, for a given alloy, the elongation decreases with ageing time at 180°C, but increases slightly with overageing (see Figure 4). These data are inversely related to the strength data presented in Figure 2. Thus, the highest formability for all alloys would be expected in the T4 condition, with an overaged (T8) temper providing increased formability as compared with extrusions in the T6 condition. In addition, AA6082 extrusions would be expected to exhibit reduced formability as compared with those of AA6063 and AA6005A alloys for a given temper. Also shown in Figure 4 are the r/t data from simple bend testing, which generally show the same effects of alloy composition and temper on formability.

A further measure of a material's formability is the "springback" following a forming operation. "Springback" may be related to the stress-strain behaviour of a material (shape of the stress-strain curve); the yield stress, tensile strength, elongation to failure and elastic modulus at relatively low strains all influencing the level of "springback" [5]. In the present work, a very basic analysis of the relevant tensile data and the level of "springback" has been performed, in which "springback" following bending was found to increase with both strength (ageing) for a given alloy and with the inherent strength of the alloy, i.e., the level of "springback" increases for a given temper as follows: AA6063 gives reduced "springback" as compared with AA6005A, which is in turn lower than AA6082. Thus, the lowest "springback" for all alloys would be expected for extrusions in the

T4 temper, with an overaged (T8) temper giving reduced "springback" as compared with extrusions in the T6 temper.



(a) (b)

Figure 4 - The effects of temper on: (a) elongation, and (b) r/t data for 6XXX alloy extrusions.

The effects of alloy composition and temper on the "deformability" of hollow, extruded sections have been determined using crush testing, following which the extent of "splitting" or fracture has been assessed in a semi-quantitative manner. This test may be related to the impact condition of a crash, as it has been shown that the 6XXX alloys exhibit little strain rate sensitivity [6]. The average crush force data for the alloys in different tempers are given in Table 1, in which the effects of alloy composition and ageing can be seen to be consistent with the strength data shown in Figure 2, as may be expected. Also shown in Table 1 are data for an additional overageing heat treatment of 20 hours at 210°C.

Alloy	T4	1 hr @ 180°C	2 hrs @ 180°C	6 hrs @ 180°C	8 hrs @ 210°C	20 hrs @ 210°C
AA6063	35.6	44.7	56.2	60.4	50.8	47.0
AA6005A	43.4	64.1	71.1	69.6	58.4	57.6
AA6082	56.0	77.5	77.2	75.7	62.7	61.6

Table 1 - Average crush force (kN) for 6XXX alloy extruded sections in different tempers.

A photograph of crushed sections of the AA6082 alloy in the T4, T6 and T8 tempers is shown in Figure 5, in which the very severe "splitting" of this alloy in the T6 condition can be seen. Some through-thickness fracture and displacement of the initial fold, and "splitting" within the folds is also observed in the T4 temper, whereas in the T8 temper, the "splitting" is confined to the corner regions of the section and within the folds only.

In contrast, crushed sections of the AA6063 and AA6005A alloys in the same tempers showed no evidence of the kind of catastrophic failure observed in the AA6082 alloy in the T6 temper (see Figure 5(b)). In the case of the AA6063 alloy, no "splitting" was observed in the T4 temper, and in the T6 temper, only minor "splits" were observed, which extended through the thickness, in the folds in the corners of the section. Also, in the T8 temper, only minor "splits" were observed which, in this case, did not extended through the thickness of the section. The AA6005A alloy also showed no evidence of "splitting" in the T4 temper, but did show some through-thickness "splits" within the folds in the T6 temper, again in the corners of the section only. However, only minor "splits" which did not extend through-thickness, were observed in this alloy in the T8 temper. A photograph showing crushed sections of the AA6005A alloy in the T4, T6 and T8 tempers is shown in Figure 6.

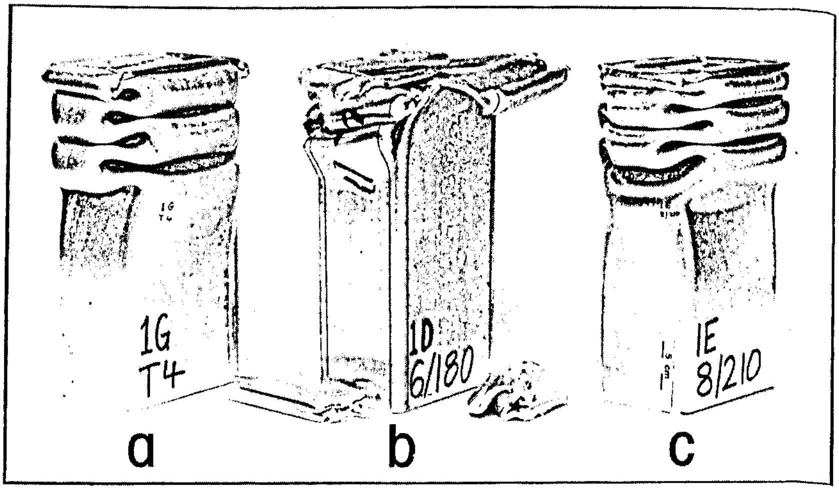


Figure 5 - Photograph showing the effect of temper on the crush, "splitting" behaviour of AA6082 extrusions. (a) T4 (as-extruded), (b) T6 (6 hrs @180°C), and (c) T8 (8 hrs @ 210°C).

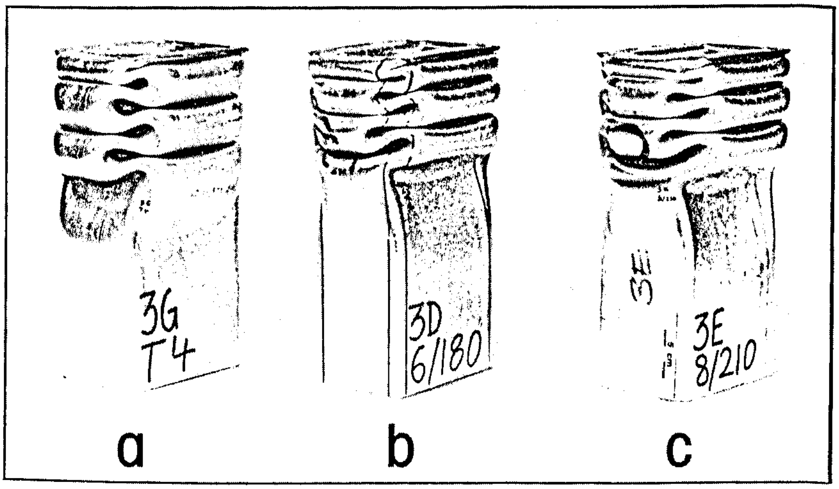


Figure 6 - Photograph showing the effect of temper on the crush, "splitting" behaviour of AA6005A extrusions. (a) T4 (as-extruded), (b) T6 (6 hrs @180°C), and (c) T8 (8 hrs @ 210°C).

Finally, the effects of a thermal exposure of 1 month at 80°C on the tensile properties of AA6063 extrusions only have been measured (see Figure 7). The data show that true thermal stability is exhibited only in the overaged temper, as may have been expected. This test is not considered unreasonable given that some components may be exposed to temperatures in excess of 80°C if close to the engine or exhaust. Also, similar "exposure" tests are used routinely in the aerospace industry. The thermal stability of the more solute-rich alloys would not be expected to behave any differently, and may in fact show reduced thermal stability as a result of the increased solute levels. It should be noted that the alloy composition differs slightly from that for which all other AA6063 data have been generated; thus, the strength levels are not equivalent to those reported in Figure 2.

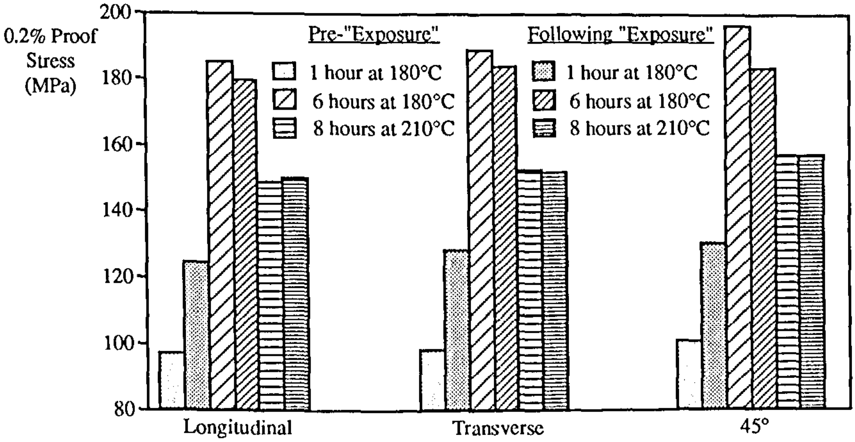


Figure 7 - The effects of a thermal exposure (1 month at 80°C) and temper on the proof stress of AA6063 extrusions, measured in the L, T and 45° orientations.

Finally, the propensity to "splitting" during crush deformation has been correlated with the relevant strength and "toughness" data, by assigning a semi-quantitative rating to crush performance. The best correlations were found for the tensile data, proof stress and elongation to failure, and the strength data and propensity for "splitting" are shown in Figure 8. However, the scatter is still considered to be too wide, and some anomalies exist (e.g. AA6082 in the T4 temper), for the data to be used as a predictive "tool" in alloy/temper selection for structural applications which require resistance to crush deformation.

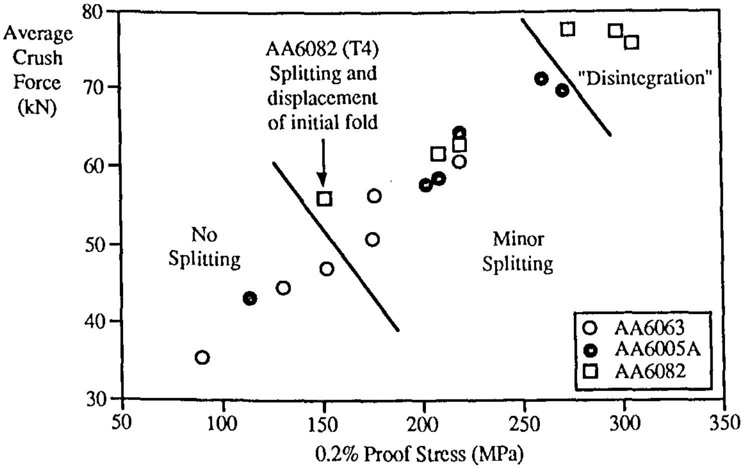


Figure 8 - The relationship between proof stress, crush force and propensity for "splitting" during crush deformation of 6XXX alloy extruded sections.

Summary and Conclusions

From the results presented in the previous section, there are several issues which need to be addressed concerning the use of 6XXX alloy extrusions in structural, automotive applications. As has been mentioned previously, the design strength of a component will, to some extent, dictate the selection of alloy composition and temper, and the shape of the component will impose formability requirements. Thus, data such as those presented here may assist the designer in the selection of alloy type and temper for a given application. However, perhaps the most significant requirement of any extruded section is that its in-service performance be predictable. In this respect, impact or crush resistance and thermal stability may be major issues; again, dependent on specific application. A structural component should exhibit in-service stability of properties (for perhaps 10 years or more), but the age hardening 6XXX alloys are, by definition, inherently unstable. Any significant change in properties with time may not be acceptable, as this will affect the ability to predict performance. Thus, it has been shown that the only temper in which true thermal stability is exhibited is that of an overaged temper. However, in the T6 temper, there is also little change in properties with time, at least for the "exposure" test applied in the present work, and such a change in properties may not be significant. Further work would be necessary to identify fully the effects of temperature and the time of "exposure" on the stability of both microstructure and properties.

Considering impact or crush resistance, the extrusions should not exhibit any form of severe "splitting" during a crash situation. However, it should be noted that the axial crush test carried out in the present work represents a very severe test of the material, although this testing is representative of the deformation behaviour expected of axial crush members (front / rear longitudinals). There are, however, many applications where the ductility and/or "toughness" requirements are less critical.

In conclusion, considering the temper in which 6XXX alloy extrusions may enter critical, structural service, the data presented here suggest the following:

1. In the as-extruded (T4) or underaged tempers, 6XXX alloy extrusions have relatively high formability and acceptable crush resistance, but very poor thermal stability. Therefore, to supply in the highly formable, T4 temper and rely upon any subsequent adhesive cure and/or paintbake cycles to strengthen would appear to be an unacceptable process route, because of the short times at temperature involved (equivalent to say 1 hour at 180°C), which would not render a component immune to further in-service ageing.

2. In the peak aged (T6) temper, 6XXX alloy extrusions have reduced formability, an element of thermal instability and, at high levels of strength, may have unacceptable crush resistance for applications such as axial crush members.

3. In the overaged (T8) temper, 6XXX alloy extrusions have reduced formability as compared with the T4 or underaged tempers, but improved formability as compared with the T6 temper, and have both acceptable crush resistance and excellent thermal stability. Obviously, the inherent alloy strength and the overageing practice can be optimised to satisfy strength requirements.

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