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# THE INFLUENCE OF BILLET PROCESSING ON THE MECHANICAL PROPERTIES OF FORGED 6061 ALUMINIUM

Martin Leary and Colin Burvill

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## 1 Introduction

The University of Melbourne, in collaboration with the local automotive and forging industry, is undertaking a research project to review the application of light alloys in safety critical automotive applications. The initial research scope was proposed in response to an identified need for component mass reduction. Mass reduction is a highly important objective for automotive design due to the associated improvement in fuel economy, dynamic performance, and emissions [1][2]. The forging partner light alloy forging as an emerging opportunity to achieve mass reduction in a mode commensurate with their manufacturing capability [3][4]. This also provided an opportunity to offset a recent loss of business to increasingly competitive casting technologies [5].

Material selection procedures developed by the authors [6][7] suggest that the optimal light alloy for this application is aluminium 6061-T6. Material selection was based on the mechanical properties of components forged from extruded 6061 billet [8][9][10]. The feasibility of light alloy substitution is highly dependant on the costs associated with billet processing [11]. Opportunities to reduce the material processing cost were identified, but the precise influence of the proposed processing on the mechanical properties of 6061-T6 are not reported in the literature. The applicability of existing data is limited as neither the processing route of the billet material, nor the level of deformation of the forged component are generally specified [12].

Before the proposed billet processing can be applied in safety critical automotive applications, its influence on mechanical properties must be quantified. An experimental procedure has been developed to quantify the influence of the proposed billet processing on the resulting mechanical properties. The risk minimisation procedures presented by the authors at the 2003 ICED conference have been applied to mitigate the risks associated with obtaining fatigue data within a design scenario with a limited timeframe [13]. Based on the experimental outcomes, the suitability of the proposed processing for safety critical automotive applications will be assessed.

## 2 Review of industry practices and literature

The mechanical and thermal processing of billet material is of significant influence to the associated capital and ongoing processing costs, and must be optimised in order to minimise component cost [11][14]. However, mechanical properties are highly dependent on microstructural parameters, including: grain size, atomic packing and dislocation density [15][16]. Therefore, opportunities to reduce the billet processing costs are only acceptable if the mechanical material properties are not degraded, or, any degradation in the resulting material properties can be justified by an improved cost-benefit outcome.

Material suppliers and tier-one forging manufacturers were interviewed to define the range of feasible processing paths for the billet material, Figure 1. The forging supplier currently specifies extruded billet material, i.e. processing path D, Figure 1. This specification is in response to a perceived consistency in the properties of extruded billet, and the mechanical properties of the resulting component. For the light alloy applied in this work, this perception is commensurate with that presented in the current forging literature [17]. The supplier does not complete periodic testing of the billet material to confirm material property consistency, nor have comparative tests been completed to confirm the influence of billet processing on the resultant component properties.

Analysis of the feasible processing paths, combined with extensive review of the available literature identified two opportunities to reduce component cost: the use of Direct Chill (DC) cast, homogenised billet, and, omission of the homogenisation process from DC cast billet processing. The proposals are presented, including associated uncertainties of the resulting material properties and the opportunities for cost reduction.

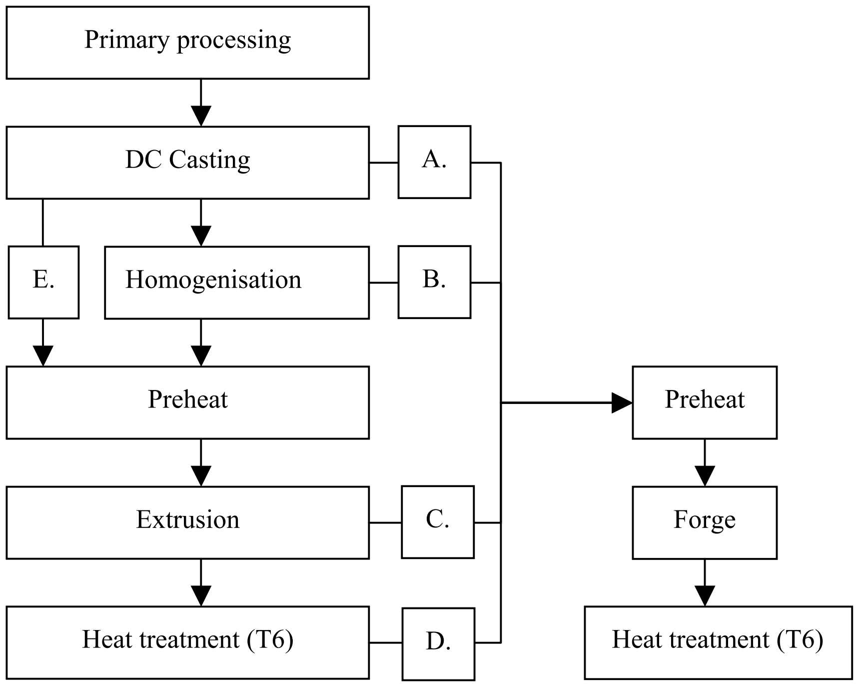


Figure 1. The feasible processing paths for the proposed material as identified by material suppliers, tier-one forging manufacturers and reference to the available literature. Processing path D is currently applied by the forging supplier. Processing path E. was identified as feasible, but was not considered cost effective by the material supplier. Processing paths A and B have been identified as opportunities to reduce the contribution of the processing path to the component cost.

## 2.1 Use of Direct Chill (DC) cast, homogenised billet

The use of Direct Chill (DC) cast, homogenised billet material presents an opportunity to reduce the associated processing costs by eliminating the cost associated with billet extrusion, i.e. processing routes B, Figure 1. However, the impact of DC cast billet material on the mechanical properties of the resulting component is ill defined. Comparative analysis of the influence of the impact of DC cast billet material on the associated material properties must be completed before the automotive manufacturer will consider substituting the existing billet material with DC cast, homogenised billet in production applications. Internal reports provided by the forging supplier and an associated billet indicate that [18][19]:

- The microstructure of specimens forged from DC cast billet material differ from specimens forged from extruded billet. Therefore, there is potential variance in microstructure sensitive material properties; and,

- Specimens forged from DC cast billet may have improved tensile properties over the extruded billet material. The microstructural basis for this performance differential has not been identified. The statistical significance of any performance differential improvement has not been defined.

Despite extensive literature review, no data was found on the relative fatigue strength of specimens forged from extruded and DC cast billet material.

## 2.2 Omission of the homogenisation process from DC cast billet processing

Homogenisation is a thermal process that controls grain size and shape to enhance material properties and extrudability[1], i.e. processing routes B, C and D, Figure 1. Homogenisation contributes significantly to the capital and ongoing processing costs [11][14]. A large number of publications are available from the extrusion industry on the influence of homogenisation on extrudability and the mechanical properties of the extruded material [14] [20-23]. The research presented by the extrusion industry may not be applicable to forging applications as, typically, when forging, the shape factor[2] is significantly less than that associated with extrusion. However, no information specific to the forging industry has been found on the influence of homogenisation on forgeability. Despite the differential in shape factor, Reiso has suggested that for forged products, the necessity of billet homogenisation is questionable as billet preheating and subsequent deformation is itself a homogenisation process, although less accurately controlled [23]. The influence of billet homogenisation on the fatigue strength of forged components has received modest attention in the available literature. The only data found to directly assess the influence of billet homogenisation on fatigue performance of forged components is Develay's evaluation of the endurance limit of 2014-T6 aluminium alloy at various levels of deformation [25][26]. No other references that address this specific topic have been identified in the available literature.

[1] Extrudability: the maximum extrusion speed before tearing of the extrudate surface [23].
[2] Shape factor: measure of the degree of extrusion difficulty. Shape factor = (final cross-section periphery ÷ initial cross-section periphery) [31]

# 3 Experimental procedure

An experimental program has been nominated to assess the influence of the proposed billet processing on the mechanical properties of forged automotive components, i.e., hardness, tensile strength and fatigue strength. Experimental procedures have been conducted in accordance with American Society for Testing and Materials (ASTM) standards, for example [27]. Based on the experimental outcomes of this work, the performance and cost differential of the proposed billet processing has been quantified, allowing unambiguous optimisation of the processing route for the application of light alloys in safety critical automotive applications.

A forming operation was developed by the forging supplier that provides consistent microstructural properties along the longitudinal direction, i.e., an extrusion operation, with a 72% reduction of area (Figure 2). A series of prototype were manufactured by the forging supplier under conditions that replicate a commercial forging scenario, the associated parameters are documented in Table 1. Prototypes were manufactured from three billet processing routes, Figure 1:

- Extruded, i.e. processing route D;
- Homogenised DC cast, i.e. processing route B; and,
- Unhomogenised DC cast, i.e. processing route A.

These specimens allowed a comparative review of the performance differential in mechanical properties that exists between components manufactured by the proposed processing routes, i.e. homogenised and unhomogenised DC cast, and the current processing route, i.e. extruded billet. The risk mitigation procedures developed by the authors [13] allowed prioritisation of the experimental procedure to maximise the certainty of outcomes within a limited time frame. The experimental outcomes are presented in the order they were evaluated, from the least risk i.e. macroscopic evaluation, to the greatest risk, i.e. fatigue strength assessment.

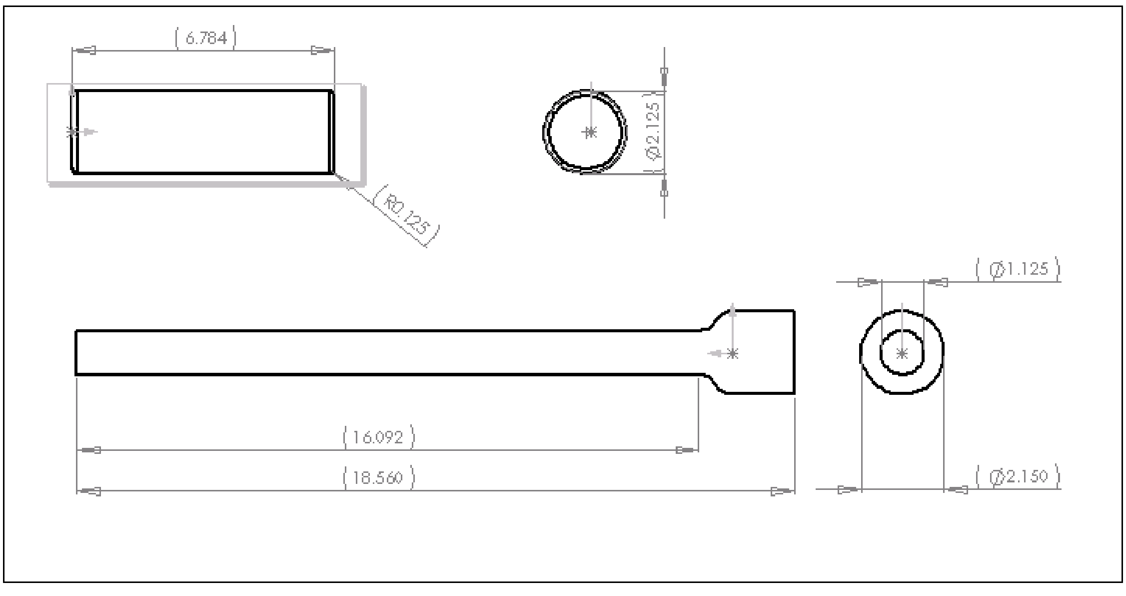


Figure 2. Initial billet geometry and subsequent extrusion. Unit of measurement: inches.

Table 1. Forging parameters.

| | |
|---|---|
| Billet forging temperature | 470°C |
| Billet heating time | 40 minutes |
| Temperature profile | Figure 3 |
| Die temperature | Uncontrolled heating by gas burners |
| Lubrication | Proprietary lubricants:<br>• Houghton hot forging agent 201<br>• Acheson Aquadag |

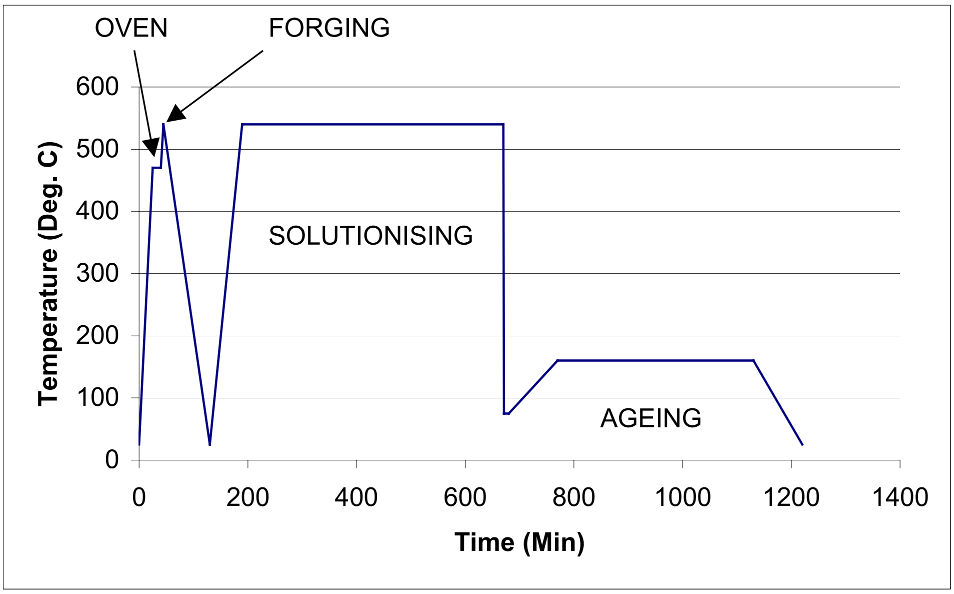


Figure 3. Billet temperature profile.

# 4 Results

Comparison of the mechanical properties for the various material processing routes quantifies the performance and cost differential between extruded, homogenised DC cast and unhomogenised DC cast billet material for forged 6061 aluminium in safety critical automotive applications. These outcomes increase understanding of the applicability of such materials, as well as providing qualitative appreciation of the influence of processing method, and subsequent microstructure, on the mechanical properties of forged 6061 components.

## 4.1 Microstructure

The microstructure of the proposed billet routes was assessed in the "as received" condition. The grain structure was assessed macroscopically in the transverse and longitudinal directions (Figures 4 and 6). The grain boundaries were revealed with a caustic soda etch (50°C for 80 seconds). The resulting grain boundaries indicate that proposed billets are macroscopically equivalent, with a fine equiaxed grain structure. This macrostructure is highly desirable, as it leads to enhanced mechanical properties and response to heat treatment [28].

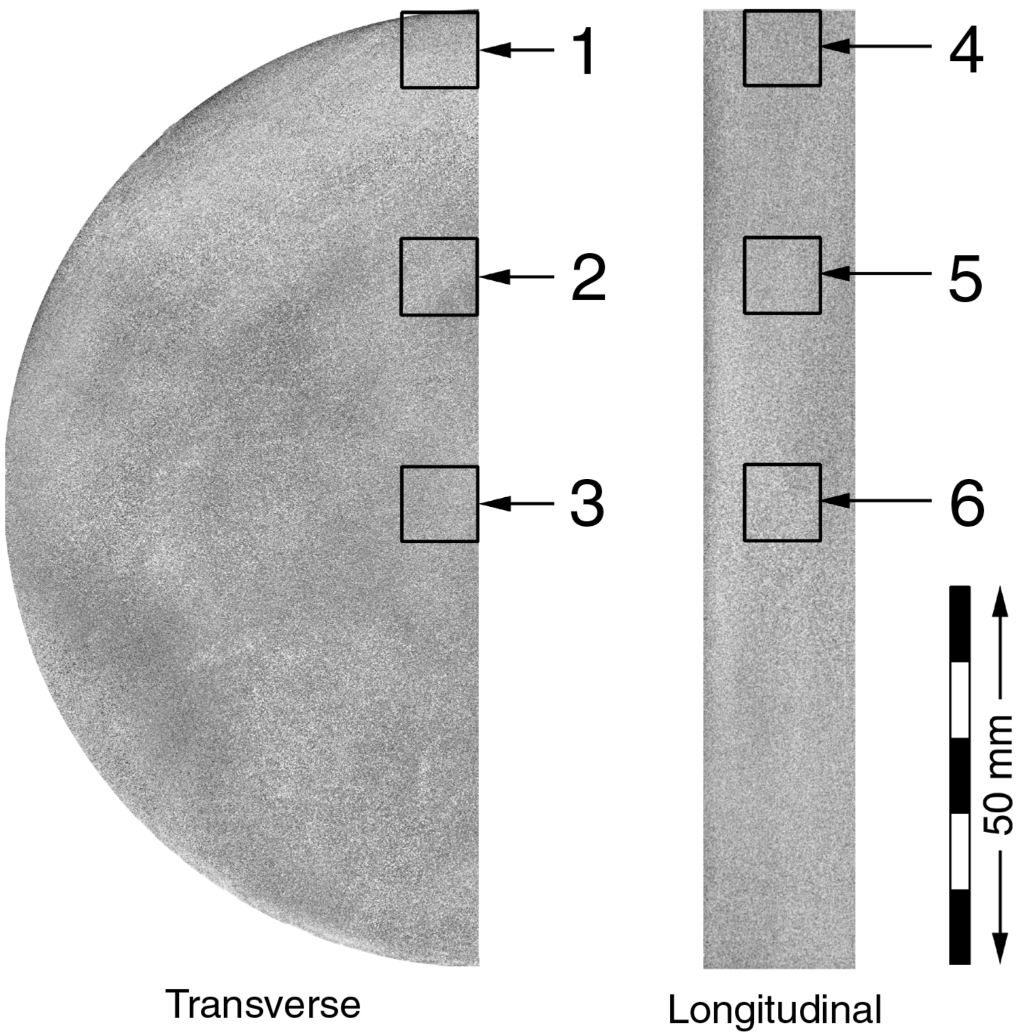


Figure 4. Homogenised billet section, caustic soda etch (50°C for 80 seconds)

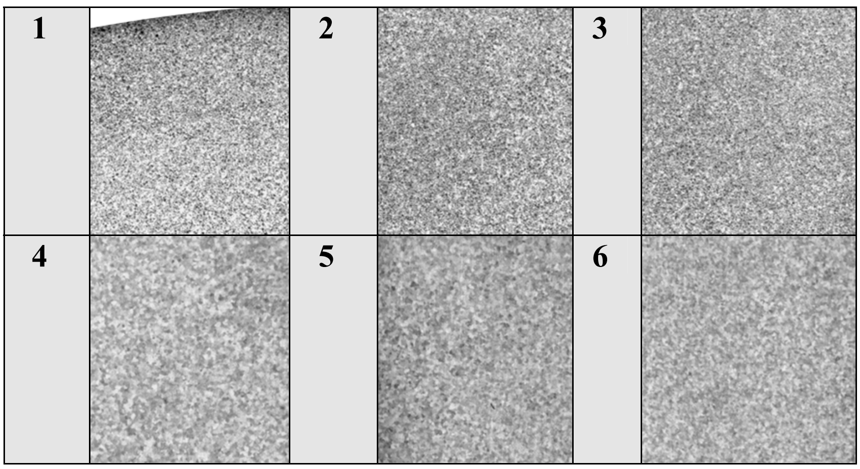


Figure 5. Three times magnification of the elements of Figure 4

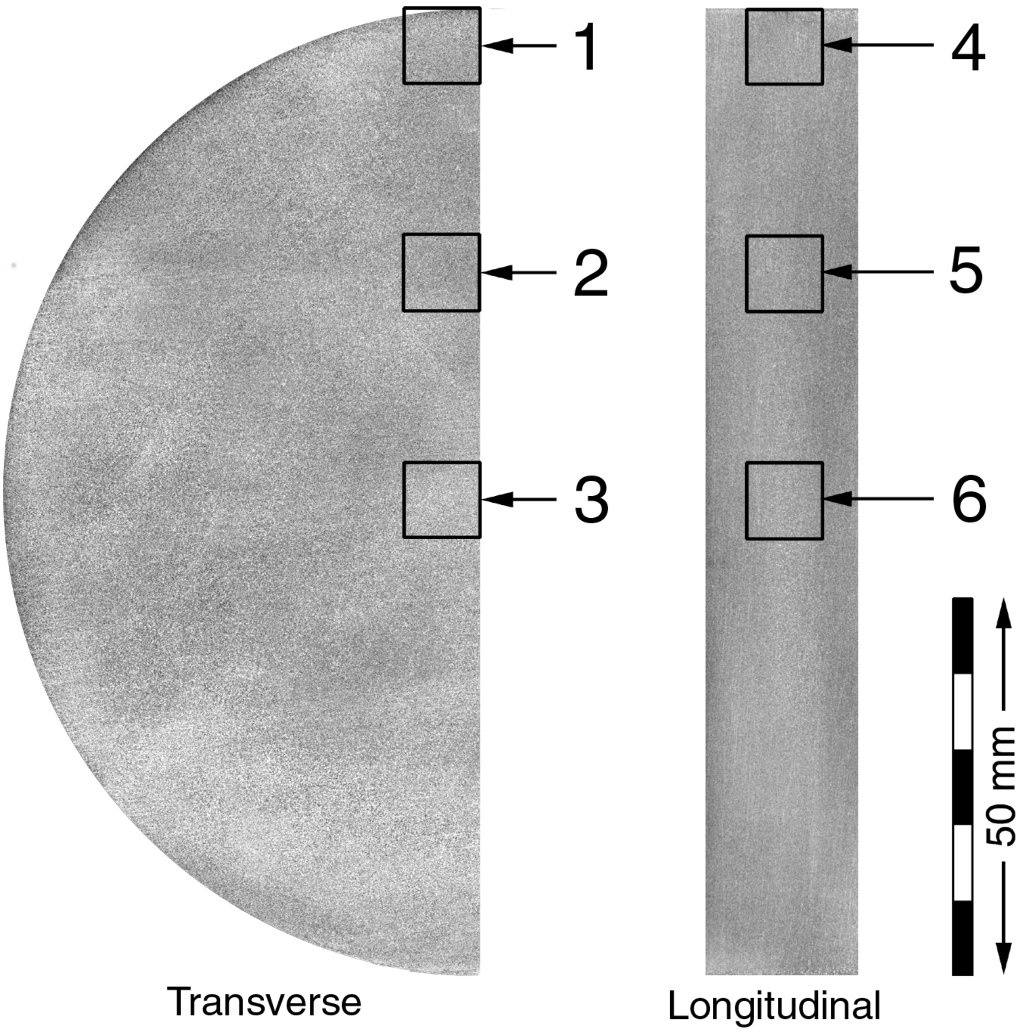


Figure 6. Unhomogenised billet section, caustic soda etch (50°C for 80 seconds)

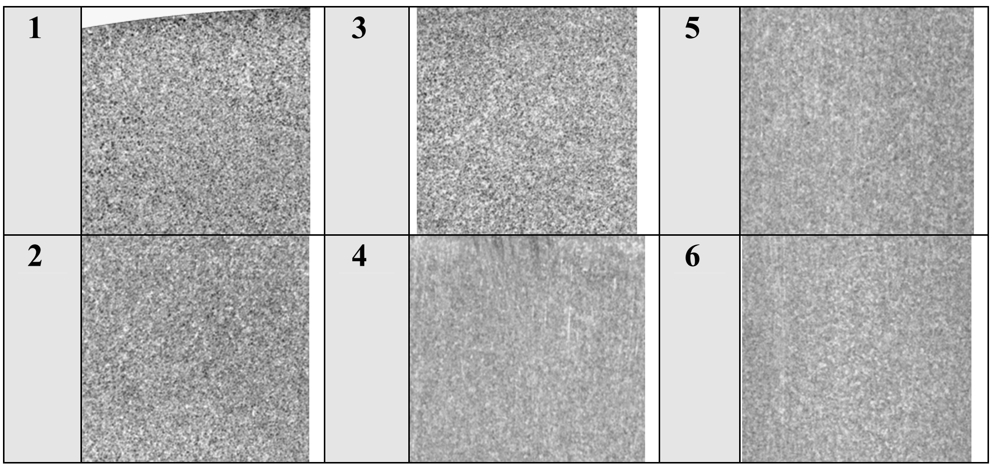


Figure 7. Three times magnification of the elements of Figure 6

Methods are available to quantify the influence of homogenisation on microsegregation, i.e. the level of inhomogeneity within a single grain, however these methods require electron microscopy that is beyond the scope of this work. As the electrical conductivity of aluminium is highly sensitive to microstructure [29], but independent of grain size, it has been applied in this work to assess the microstructural variation induced by the homogenisation process, Figure 8:

- There is significant variation in the conductivity measurements for homogenised and unhomogenised DC cast billet in the "as received" condition. The higher conductivity is suggestive of a greater level of recrystalisation in the homogenised billet [29].
- The forging process, and subsequent heat treatment decreases the conductivity of the homogenised billet, and increases the conductivity of the unhomogenised billet.
- Although the conductivity of the extruded and homogenised billet is very similar in the "as received" condition the conductivity of the extruded product is significantly greater than for the homogenised product in the finished products, i.e. forged-T6, Figure 8.

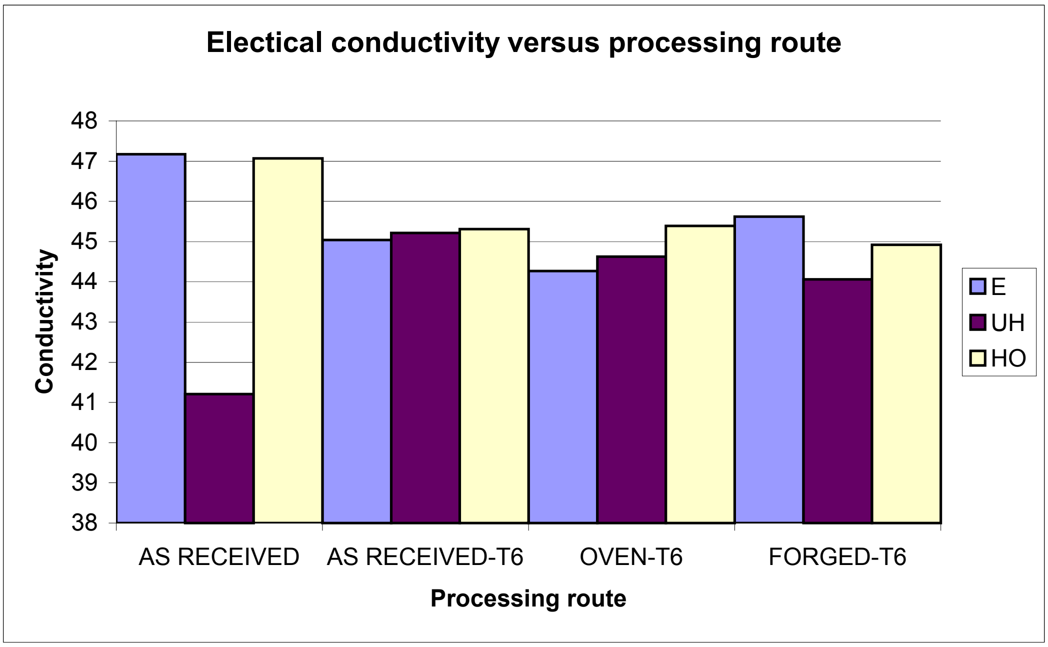


Figure 8. Electrical conductivity of test specimens versus processing route. Legend: E – extruded, UH – unhomogenised, H – homogenised.

## 4.2 Tensile strength

Figure 9 indicates the ultimate tensile strength recorded for six processing conditions for each of the proposed processing routes, for a series of processing conditions, i.e. as received, heated to forging temperature, forged, and heat treated. In general:

- The extruded material is received in a heat-treated condition. This enhanced tensile strength diminishes in during heating to forging temperature.
- Heating to forging temperature occurs at a temperature that exceeds the recommended annealing conditions, i.e. 345°C, allowing complete annealing to occur [29].
- The annealing process does not significantly change the tensile strength of the homogenised billet. This is indicative of the annealing associated with homogenisation.
- The annealing process equalises the tensile strength of the samples. There is no significant variation in the strengths associated with the different billet material at this stage of processing.
- The tensile strength reaches a minimum after heating to forging temperature in preparation for forging. The heating process Probably not an issue when heating time is very low, for example induction heating [21].
- All processing routes indicate similar tensile strength after forging. The forging process imparts some increased tensile strength, indicating that not all of the work hardening associated with plastic deformation is recovered by recrystalisation.
- Post heat treatment the extruded billet material exhibits the highest tensile strength, i.e. mean tensile strength is 295 MPa, followed by the unhomogenised, i.e. mean tensile strength is 273 MPa, and Homogenised billet material, i.e. mean tensile strength is 269 MPa.

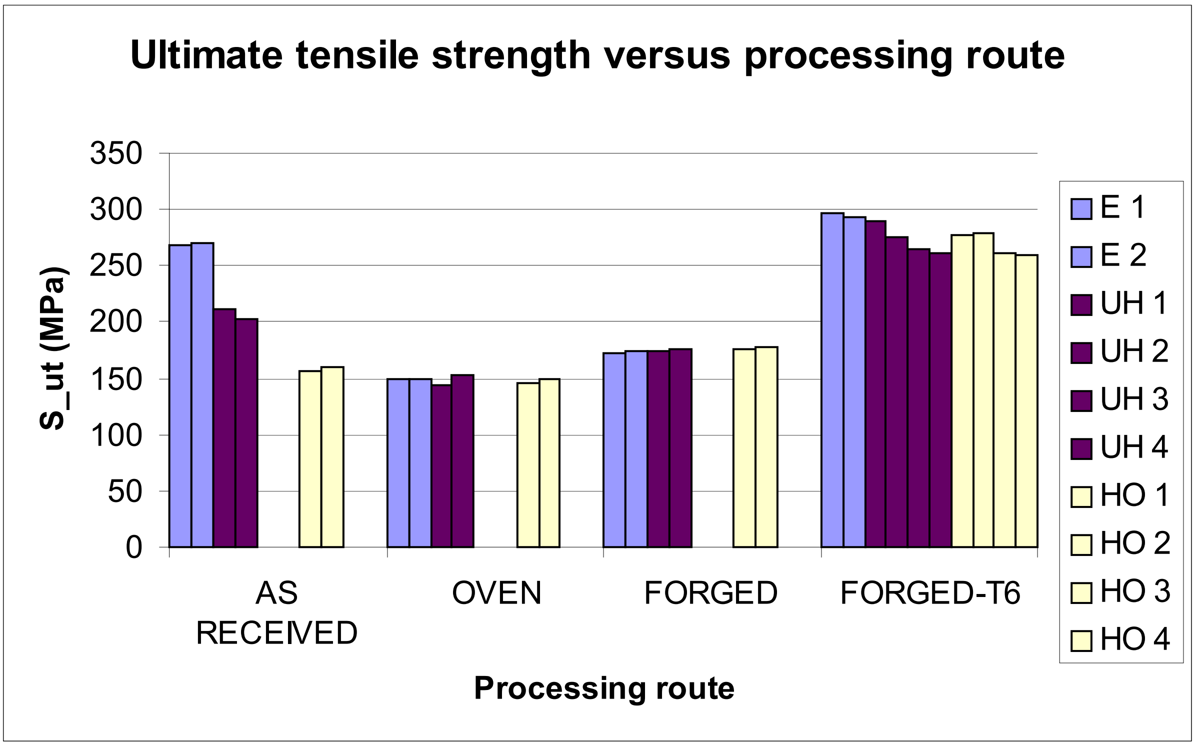


Figure 9. Tensile strength of test specimens versus processing route.
Legend: E – extruded, UH – unhomogenised, H – homogenised.

## 4.3 Fatigue strength

Fatigue can result in catastrophic failure that occurs without warning; therefore this failure mode is of significant importance to safety critical systems. Concurrently, the fatigue mechanism is highly localised, and is highly dependent on the most significant flaw in the component. Fatigue testing is therefore expensive and time consuming [8][9]. An experimental procedure was developed that allowed the influence of the proposed processing routes on fatigue strength to be quantified within the available design budget:

1. To maximise the useful outcomes, only the novel processing routes were tested, i.e. unhomogenised DC cast billet and homogenised DC cast billet.
2. Discussion with the automotive manufacturers identified the most important fatigue life to occur at 100, 000 cycles, i.e. 1.0 E5 cycles, therefore testing was restricted to this fatigue life.

To minimise the observed scatter in fatigue strength, and to maximise the applicability of the test results, the fatigue specimens were polished to minimise the influence of geometric stress concentrations. The selected criterion for determining acceptable surface finish was based on the ASTM case study, that specifies that "no circumferential machining should be evident when viewed at approximately 20 times magnification under a light microscope" [27]. Literature review identified a lack of consistency in experimental methods and documentation used in fatigue testing [30]. To assist repeatability the test procedures and nomenclature is based on ASTM standards [27]. A robust and systematic sample preparation procedure was applied:

1. CNC machine sample to nominal specimen geometry (Figure 8);
2. Clean sample with alcohol and dry with compressed air;
3. Rotate sample slowly (60 RPM) in a lathe and grind circumferentially for 150 revolutions with 1200 grit SiC paper;
4. 50mm diameter felt pad disk generously impregnated with 3 micron diamond paste and lightly lubricated;
5. Rotate sample slowly (60 RPM) in a lathe and simultaneously polished longitudinally with a felt pad disk rotated at high speed (5000 RPM) for 100 seconds;
6. Repeat steps 4 – 5 a total of four times.
7. Clean sample with alcohol and dry with compressed air;
8. View sample at 20 times magnification under a light microscope confirm that no circumferential machining is evident (Figure 8).

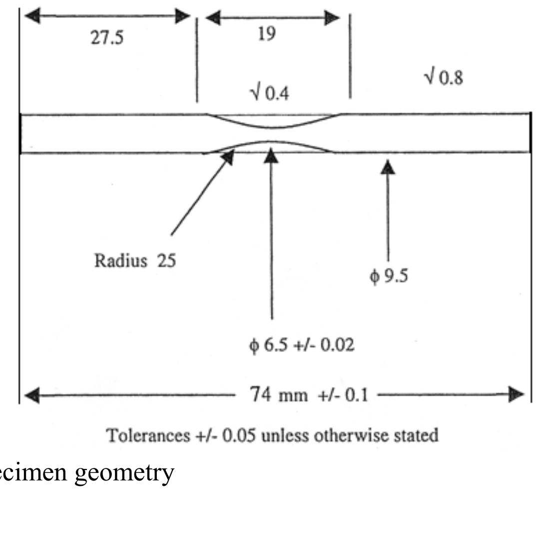


Figure 10. Fatigue strength specimen geometry

The test specimens were tested on a rotating beam apparatus that applies a controlled rotating bending to the specimen gauge section and records the number of cycles to failure. The resulting fatigue strength is presented with a series of S-N curves for 6061-T6 aluminium published in the literature, Figure 9. The fatigue strength:

- Shows a very low variance in the observed fatigue life;
- Falls within the range expected from the literature for both processing paths [8][9]; and,
- The performance of the unhomogenised material, i.e. the mean fatigue life at 205 MPa is 7.3 E5 cycles, is greater than for homogenised material, i.e. the mean fatigue life at 205 MPa is 5.5 E5 cycles.

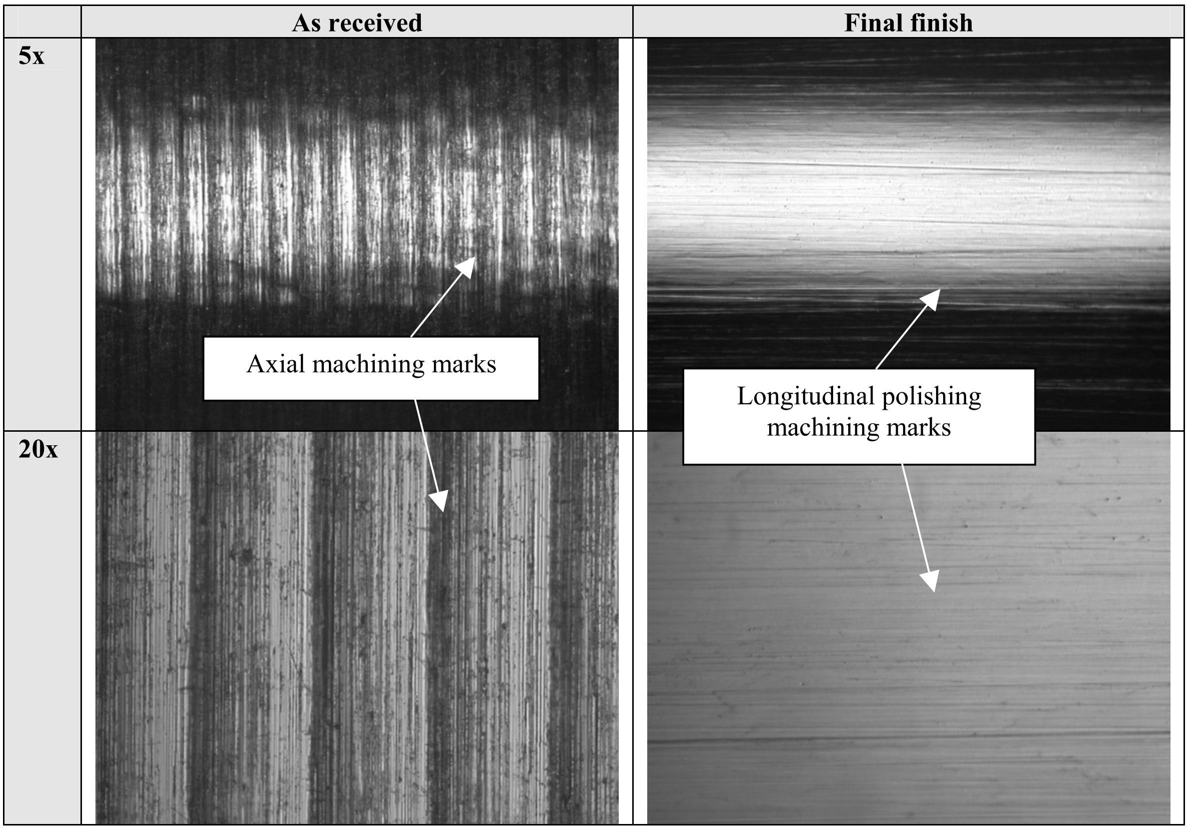


Figure 11. As received and final finish of fatigue specimens

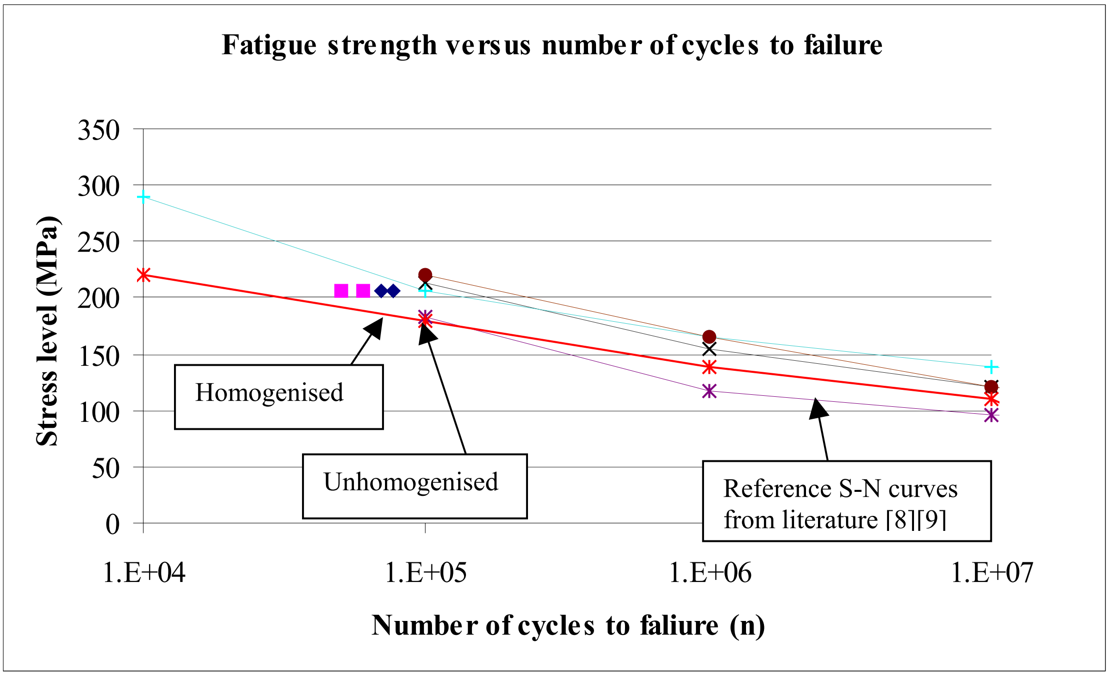

Figure 12. Fatigue strength of the proposed processing routes and samples available from the literature.

# 5 Conclusions

Experimental assessment of forged 6061-T6 aluminium components in a series of processing conditions has quantified the relationship between billet processing and the resulting mechanical properties. The most significant outcomes for safety critical forged automotive application are:

- Tensile strength is maximised with the processing path currently in use. This outcome validates the prevalence of this processing route in industrial applications [17].
- The electrical conductivity and tensile strength of both homogenised and unhomogenised DC cast billet is equalised after heating to forging temperature.
- The subsequent difference in the tensile strength associated with homogenised DC cast billet and unhomogenised DC cast billet is minimal after forging and heat treatment. This outcome validates the hypothesis that the homogenisation process is redundant for some forging scenarios [23].
- Of the proposed processing paths investigated, the tensile strength of unhomogenised billet is slightly greater than that associated with homogenised billet.
- The fatigue life of both unhomogenised billet and homogenised billet lies within the range expected from the literature for the proposed material [8][9]; and,
- The fatigue life of unhomogenised DC cast billet is greater than for homogenised DC cast billet, i.e. 7.3 E5 cycles and 5.5 E5 cycles respectively.

The results indicate that the proposed processing paths reduce the mechanical properties of the forged product. This work quantifies the reduction in mechanical properties and can provide a basis for assessing the associated cost-benefit of the proposed processing paths. The unhomogenised DC cast billet is mechanically to the homogenised DC cast billet, as the unhomogenised billet requires fewer processing phases than the homogenised billet, it is evident that unhomogenised DC cast billet has the greatest cost-benefit for forged light alloy applications.

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Martin Leary
University of Melbourne
Department of Mechanical and Manufacturing Engineering
Parkville 3010 Victoria, Australia
Phone: +61 3 8344 6658
E-mail: martinleary@sweptpath.com