SEVENTEENTH EUROPEAN ROTORCRAFT FORUM

ALUMINIUM-LITHIUM ALLOYS - APPLICATION ON HELICOPTERS

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September 24-27, 1991, Berlin, Germany
Deutsche Gesellschaft für Luft-und-Raumfahrt e.V.(DGLR)
Godesberger Allee 70, D-5300 Bonn 2, Germany

ALUMINIUM-LITHIUM ALLOYS - APPLICATION ON HELICOPTERS

by

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ABSTRACT

Because rotorcraft are usually more weight-critical than their fixed wing counterparts, the lower density of aluminium-lithium alloys is particularly attractive for helicopter structural applications and will therefore be used extensively on the Anglo-Italian EH101 helicopter. In order to minimise costs, the necessary qualification and certificate procedures have been shared by the two collaborative partners in this project, with AGUSTA having taken responsibility for evaluating sheet material whilst WESTLAND have dealt with extrusions and forgings. Corresponding plate will not be used due to unacceptably low fly : buy ratios.

The approach toward aluminium-lithium sheet has been to develop both 'damage tolerant' and 'medium strength' categories from a single starting temper by alternative artificial ageing treatments, with target property levels being those of the 'conventional' aluminium alloys being replaced. With regard to forgings, the critical dependence of properties upon processing parameters and microstructure has been recognised and has entailed extensive testing of each forging configuration to be used. All sheet, extrusions and die forgings for construction of the main cabin frame are made from the 8090 'ingot metallurgy' aluminium-lithium alloy. In addition, a small number of components and specifically those comprising the undercarriage assembly, will be made from the 'powder metallurgy' aluminium-lithium Al-905XL alloy.

Whilst investigations and property characterisation is continuing, the extensive studies carried out so far have generated sufficient data and confidence to enable construction of the EH101 to proceed using these new alloys. This paper details some of the work carried so far and the generated data has facilitated preparation of joint AGUSTA-WESTLAND material specifications, necessitated due to the current lack of National and International documents. There is no doubt that the EH101 will emerge as the first aluminium-lithium helicopter.

1. INTRODUCTION

It is believed that the EH101 will represent the first time that aluminium-lithium alloys have been used for the construction of helicopter airframes. Although initially intended to save approximately 55 kg of the main cabin frame by direct substitution of these alloys,which show a 8-10% density reduction and ~10% modulus increase over their 'conventional' counterparts, the increasing confidence gained as testing has continued has now led to the decision to incorporate aluminium-lithium alloys throughout the EH101 airframe to give structural weight savings in excess of 200 kg. Because the original EH101 design pre-dated the commercialization of the new aluminium-lithium alloys, 'conventional' aluminium alloys were initially specified and it is at such property levels that the new 8090 alloy in sheet and extruded forms has been targetted by the adoption of appropriate thermo- mechanical treatments and subsequent artificial ageing conditions. For sheet components, 8090 in the recrystallised condition will be used for 'damage-tolerant' applications (replacing 2024-T3 and corresponding to BSL109) as well as those requiring 'medium strength' properties (replacing 2014A-T6 and corresponding to BS L165): these different property categories will be achieved by the use of alternative artificial ageing conditions applied to a common 8090-T3 starting stock, a condition in which trials have indicated that typical EH101 parts can be made by most forming processes. Rolled 8090 sheet will be used down to the commercially-available lower limit of 0.6 mm while current work is assessing the feasibility of chemi-milling to thinner gauges for construction of honeycomb structures. A small number of components will additionally be made from superplastically formed 8090 sheet. Other aluminium- lithium alloys in sheet form such as 2090 for high strength applications (to replace 7075-T76 or 7475-T76) and 2091 as an alternative for 8090C are still under evaluation.

With regard to extrusions, over forty different profiles have been identified and will be manufactured in unrecrystallised 8090 in which properties match those of the 7075-T74511 (≡ BS L160) alloy being replaced. An additional advantage of 8090 is its enhanced extrudability compared to other 'strong' aluminium alloys and this is being exploited to produce a one piece hollow section seat track to replace a bonded assembly made from 7075 extrusions.

For 'heavier' sections, many EH101 components were originally designed in 7010-T7451 plate (to DTD 5130A), but a weight saving cost analysis has concluded that due to a combination of low materials utilisation (i.e. low fly : buy ratio) and the higher price of aluminium lithium alloys (typically 3-5 times that of their 'conventional' counterparts), use of 8090 plate cannot be justified on grounds of cost. Accordingly, numerous parts will now be manufactured from 8090 cold compressed die forgings on the premise that the extra initial costs of forging die manufacture will be offset by the reduced machining costs to produce the final component, compared to that of plate. Extensive studies have shown that cold compressed 8090 die forging properties do not exhibit the same combination of properties as 7010, the latter generally exhibiting higher static strength and toughness whilst the former is superior with regard to fatigue and crack growth behaviour. An analysis of the main cabin frame has concluded that lower strength levels are acceptable provided that fatigue properties are not compromised, thus enabling 8090 to be used in the form of cold compressed die forgings for this application. Comparable strength to 7010 alloy is nevertheless required for certain other components and it is in such cases that the mechanically alloyed, non-heat treatable Al-905XL 'powder-metallurgy' aluminium lithium alloy will be used.

Table 1 summarises the main use of aluminium-lithium alloys on the EH101.

2. ALUMINIUM-LITHIUM ALLOY 8090 SHEET

2.1 Room Temperature Design Allowables

In order to satisfy airworthiness certification requirements, design allowables have been derived according to MIL-HDBK 5 "computation of derived properties" procedures wherein testing of a minimum of 10 lots of different thickness (within the range of interest) or different production heat (minimum 2 heats) is stipulated in order to take into account batch variability. Test results generated so far on 12 material lots for 8090C-T81 damage tolerant condition sheet are shown in figures 1-5 and cover the static properties for which allowables are usually required. Analysis of the data has indicated satisfactory levels of scatter and the applied statistical analysis has given design allowables equivalent to those of clad 2024-T3 sheet. Because of the propensity of 8090 in certain conditions to exhibit significant anisotropy of mechanical properties, this has also been assessed with the current material and has been included in the above tests by inclusion of property determinations at a 45° in-plane angle. These studies confirm that the choice of the recrystallised (as opposed to unrecrystallised) condition generates properties in which the anisotropy is no worse than in 2024-T3 sheet. Figures 6 and 7 show the anisotropy ratios for ultimate and yield strengths.

2.2 Engineering Properties

Other engineering properties which are subject to batch variability have also been assessed. Figure 8 indicates that the AGUSTA-WESTLAND 'damage tolerant' 8090C-T81 elongation minimum of 8% is achieved in the majority of cases which is a considerable improvement upon the 3% level typically achieved in unrecrystallised 8090 sheet. Figures 9 and 10 demonstrate that elastic modulus and density levels respectively are very consistent from batch to batch and analysis has confirmed a modulus increase greater than 9% and a corresponding average density decrease of 8.5% compared to clad 2024 sheet. In the case of fatigue properties, the adopted approach has been to perform comparative tests with clad 2024-T3 sheet in the form of rivetted specimens. The results are shown in figure 11. Because it is the intention to replace clad 2024-T3 with unclad 8090-T81, particular attention has been paid to the corrosion protection and fatigue behaviour under corrosive conditions. Figure 12 shows the results of fatigue tests carried out in such a corrosive environment (3% NaCl solution) using primed specimens with local primer damage in the form of a longitudinal scratch.

2.3 Forming Characteristics

A significant amount of effort has been directed at the formability characteristics of 8090C-T3 sheet since both 'damage tolerant' and 'medium strength' components will be made from this common starting material. The results of a series of bend tests are shown in figure 13 and although some degree of scatter is apparent as a function of sheet thickness, the 8090-T3 (i.e. supply conditions) sheet invariably exhibits comparable or superior formability compared to that in 2024 sheet in the W condition. This is clearly advantageous on cost grounds as it allows forming of small radii in the "as supplied" condition without the need for any re-solution treatment. The enhanced forming characteristics of 8090C-T3 have been convincingly demonstrated by the manufacture of the component shown in figure 14 which was originally designed in 0.64 mm clad 2024-T3 but formed in the re-solution treated, W, condition as it had previously been shown to be impossible in the T3 temper. A comparison was conducted beween 0.64 mm 8090C-T3 and 2024-W sheet and as shown in figure 15 the latter shows some flange waviness in the compression area of the joggles which did not occur in 8090C-T3.

To evaluate the forming limits and to confirm results of bend tests, the same component was made with 2.3 mm thick sheet. In this case, the component was readily made from the 8090C-T3 sheet whereas that in 2024-W exhibited cracks in the corner regions, figure 16.

3. ALUMINIUM-LITHIUM FORGINGS

As mentioned in the Introduction, cold compressed die forgings in 8090 alloy will be used to manufacture all components comprising the main cabin frame in place of 7010-T7451 plate. A total of 14 different forging configurations are being manufactured from which the 38 components required for the main cabin frame will be machined. Because of the critical dependence of properties upon post-solution treatment cold working in 8090 alloy, close attention has been paid to achieving as uniform a degree of cold compression as possible in these forgings. This is now being achieved by the use of specially designed cold compression dies although extensive testing of each specific forging configuration is nevertheless being carried out, both to ensure that adequate properties are being achieved throughout each forging type as well as to build up a statistical data base of properties. In addition to static strength and ductility, the following properties are also being extensively studied:-

- Notched and un-notched fatigue
- Plane strain fracture toughness
- Stress corrosion
- Intergranular and exfoliation corrosion
- Anisotropy in mechanical properties
- Density
- Crack Growth Rate (da/dn curves)

Figure 17 shows typical EH101 forgings in 8090 (cut in half in this case prior to laboratory evaluation) and figure 18 demonstrates graphically the mean tensile and ductility values which have been obtained for trial 8090-T852 forgings. These show clearly that the minimum levels set by WESTLAND designers and the original 7010 plate specification minima are readily achieved and exceeded and every confidence exists that subsequent forging configurations will behave similarly, although extensive testing will nevertheless continue. Apart from strength, the other most important property is fatigue and tests have shown that this is at least as good, and frequently superior, to both trial 7010-T736 forgings and 7010-T7451 plate previously tested. In addition to the above tests, microstructural studies are also being made using optical, scanning and transmission electron microscopy with full EDS analytical facilities in order to monitor features such as grain size and structure, undissolved intermetallic particle type, shape, size and distribution and fractographic characteristics.

It cannot be emphasised too strongly the importance of achieving adequate cold compression (nominally 4%) in order for satisfactory mechanical properties to be achieved. Extensive WESTLAND work has confirmed this and the affect upon strength and ductility is summarised in figure 19. For sufficient cold work to take place, it is important to appreciate the reason for doing so - it is to introduce a dislocation network upon which the necessary S-Al_2CuMg strengthening phase can nucleate. Metal shearing is therefore a prime requisite for which two physical factors must be satisfied. Firstly, there must be sufficient metal to be sheared which places limitations on the minimum thickness of components. Secondly, the shape of the forgings must be such that metal is able to move and is not constrained by adjacent regions, thus placing constraints on the configuration of forgings. Clearly, the forgings for the main cabin meet both the above requirements but certain other components do not. Examples of the latter include the EH101 undercarriage cylinders which, if made in aluminium lithium, could offer significant structural weight reductions. Because of the bulk and shape of these components, cold compression would be largely ineffective, with the result that if made in 8090, properties would not be adequate which, in this case, <u>must</u> match 7010-T736 (to DTD 5636) ultimate strength levels. For these applications, WHL tests have shown that the 'powder metallurgy' aluminium-lithium alloy designated Al-905XL is capable of achieving the required properties. This is an aluminium-lithium-magnesium alloy in which powders of the constituent elements/master alloys are placed in a ball mill or attritor and by a process of repeated solid state welding and subsequent microfracture eventually lead to fine powder particles of the desired composition. This process is known as mechanical alloying. The powders are then hot pressed, vacuum degassed and extruded to provide 100% consolidation. The resulting billet is then forged. In order to prevent the powders welding together to form one solid mass during the ball milling process, an organic lubricant is added. During subsequent hot pressing this breaks down to form carbon, hydrogen and oxygen, the hydrogen being removed by degassing while the carbon and oxygen form a dispersion of fine aluminium carbides and aluminium oxide particles which provide a dispersion strengthening effect in the alloy. The result is that the material does not need heat treatment, thus providing benefits in that distortion and straightening problems are avoided, quench sensitivity effects in thick sections are absent and the need for cold compression is entirely removed. Figure 20 shows a trial EH101 nose landing gear cylinder in alloy Al-905XL and whilst property evaluation of this component is in progress, corresponding data from an associated torque link in this alloy has been generated and is summarized schematically in figure 21 in which 7010-T736 (DTD 5636) strength levels are readily achieved. It has been decided that Al-905XL will be used for both the nose and main landing gear cylinders on the EH101, the upper and lower torque links, castor and cross beam. Further components are currently being reviewed for similar conversion.

4. SUMMARY

Extensive work has been carried out to qualify the new aluminium-lithium alloys 8090 and Al-905XL in order to effect significant structural weight reductions on the EH101. Alloy 8090 in sheet form will be procured in the T3 temper and alternative artificial ageing treatments will enable both 'damage tolerant' and 'medium strength' properties to be achieved. Statistically derived design allowables have been generated and comparison of other engineering properties show that they match those of the 2024-T3 and 2014A-T6 alloys which they are to replace. Alloy 8090 has the added advantage that formability in the T3 temper is superior to that of 2024-T3 and 2024-W.

Extruded sections in 8090 will be used to replace alloy 7075 and over 40 sections have been identified for conversion. The enhanced extrudability of 8090 has also resulted in a one piece hollow section extruded seat track replacing a previously bonded assembly using 7075 extrusions.

Cold compressed die forgings in 8090 will be used for construction of the EH101 main cabin frame utilising 38 different components machined from 14 forging configurations. For components whose size and/or shape do not lend themselves to effective cold compression, the mechanically alloyed Al-905XL 'powder metallurgy' alloy will be used, in which heat treatment is not needed to achieve properties comparable to 7010-T736 forgings. The decision has been made that the undercarriage assemblies will use this alloy and other possible applications are being reviewed.

As a result of the continuing close collaboration between Materials Departments at AGUSTA and WESTLAND, there is now no doubt that the EH101 will emerge as the Worlds first aluminium-lithium helicopter.

PRODUCT FORM	ALUMINIUM-LITHIUM ALLOY	SUBSTITUTE FOR:-
Sheet (Damage Tolerant)	8090C-T81 8090C-T621	2024-T3 (≡ BS L109) 2024-T4 (≡ BS L110)
Sheet (Medium Strength)	8090C-T8	2014A-T6 (≡ BS L165)
Cold compressed die forgings	8090-T852	7010-T7451 (plate to DTD 5130A)
Non-cold compressed die forgings	Al-905XL	7010-T7451 (plate to DTD 5130A) 7010-T736 (forgings to DTD 5636)
Extruded sections	8090-T8511	7075-T74511 (≡ BS L160)

Table 1 - Aluminium-Lithium product forms on the EH101.

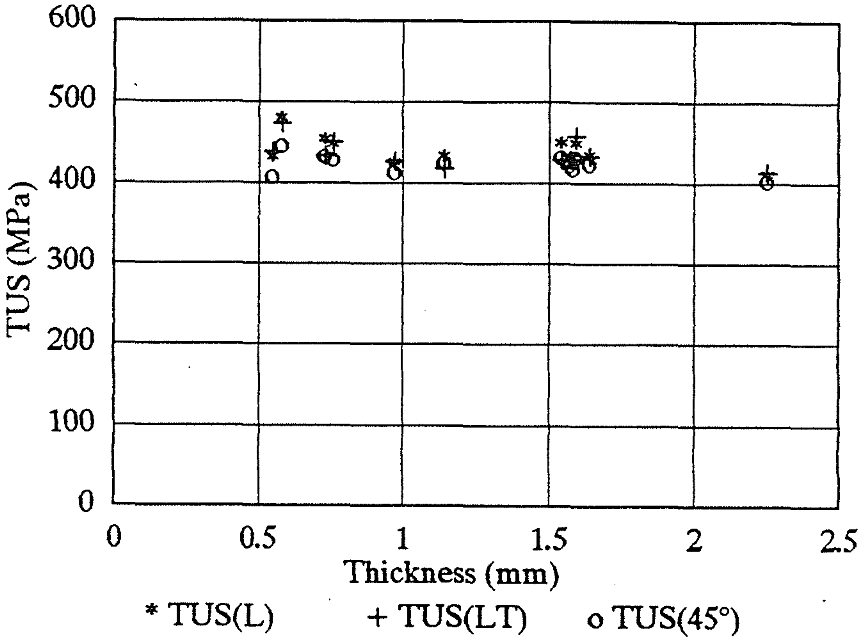


Figure 1. Sheet qualification tests: Ultimate Tensile Strength in three different directions for various production lots.

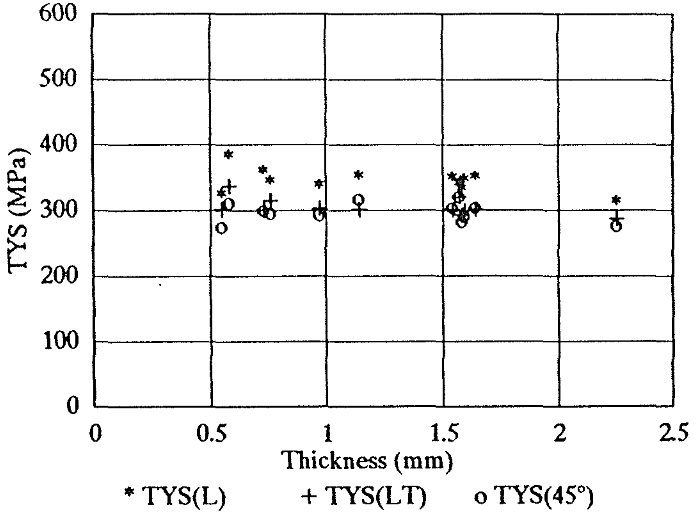


Figure 2. Sheets qualification tests: 0.2% P.S. in three different directions for various production lots.

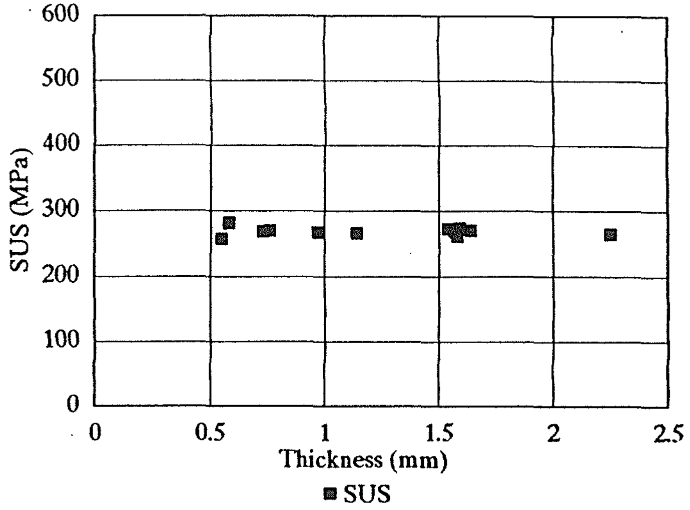


Figure 4. Sheet qualification tests: Ultimate shear strength in three different directions for various production lots.

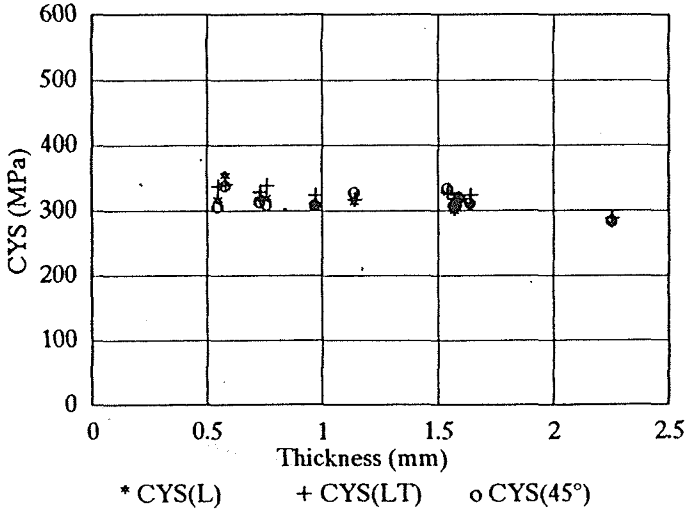


Figure 3. Sheet qualification tests: Compression 0.2% P.S. in three different directions for various production lots.

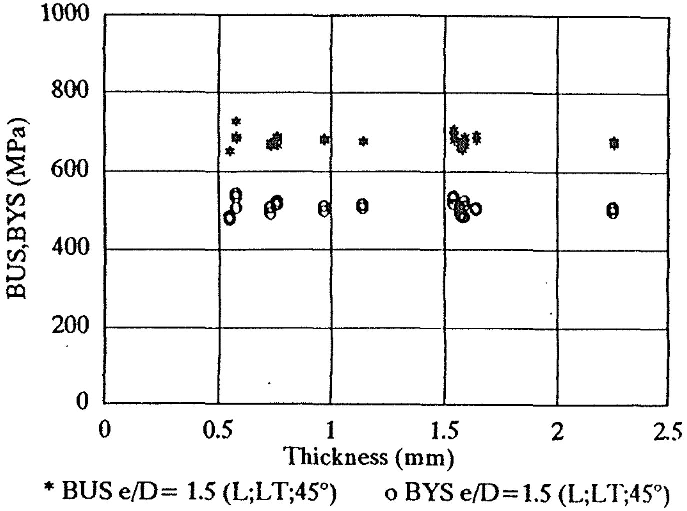


Figure 5. a) Sheet qualification tests: Bearing strength in three different directions for various production lots.

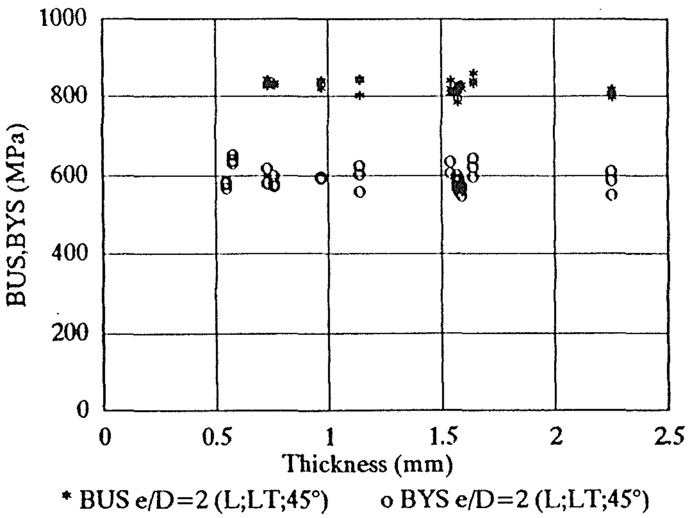


Figure 5. b) Sheet qualification tests: Bearing strength in three different directions for various production lots. e/D = 2.

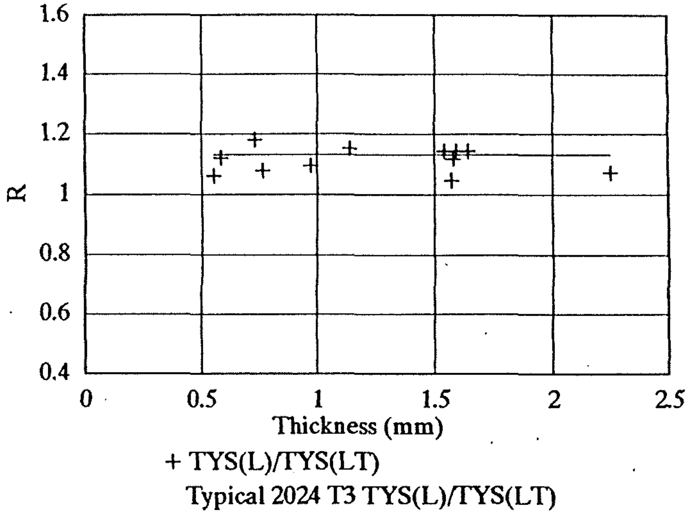


Figure 7. Anisotropy ratios of 0.2% PS in L and LT directions with 2024-T3 for comparison.

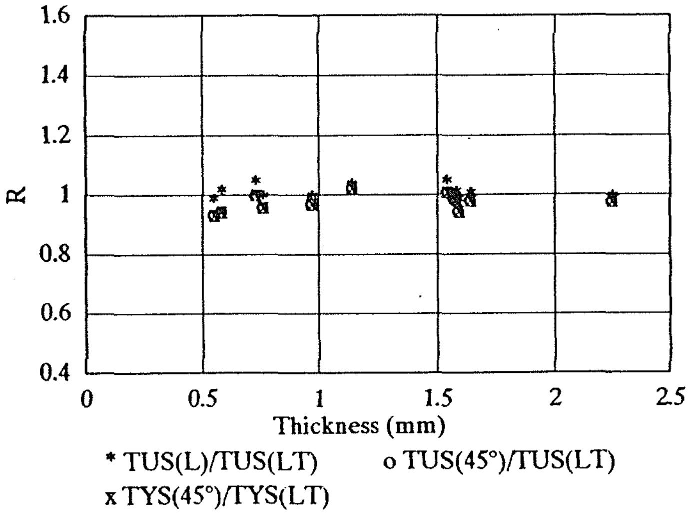


Figure 6. Anisotropy ratios of ultimate strength in L, T and 45° orientations.

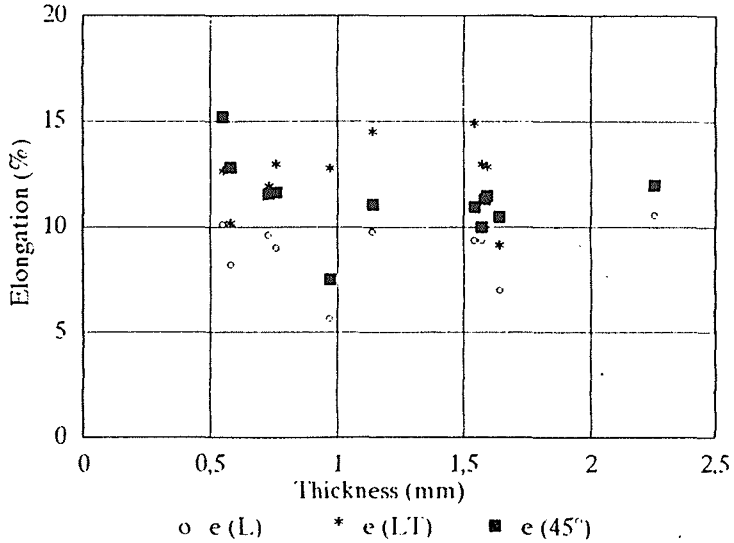


Figure 8. Engineering properties: Elongation in different directions.

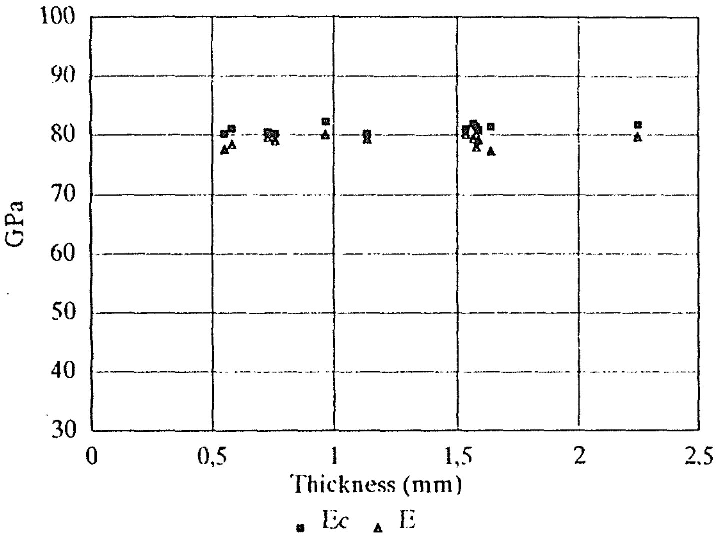


Figure 9. Engineering properties: Tensile and compressive Moduli.

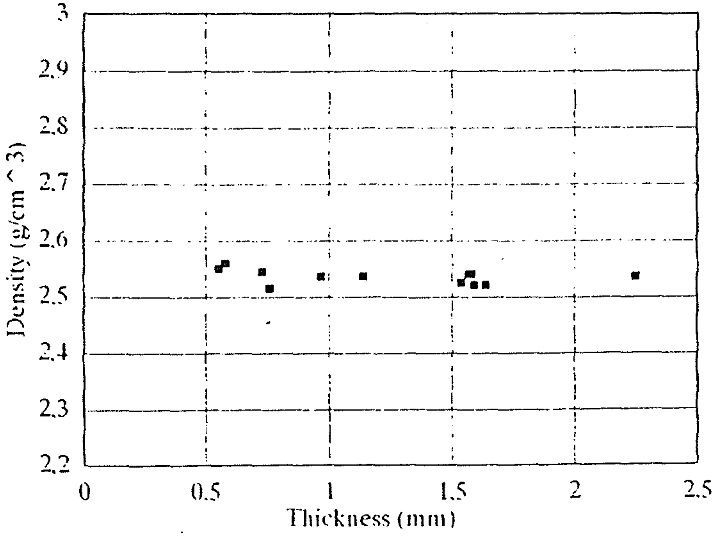
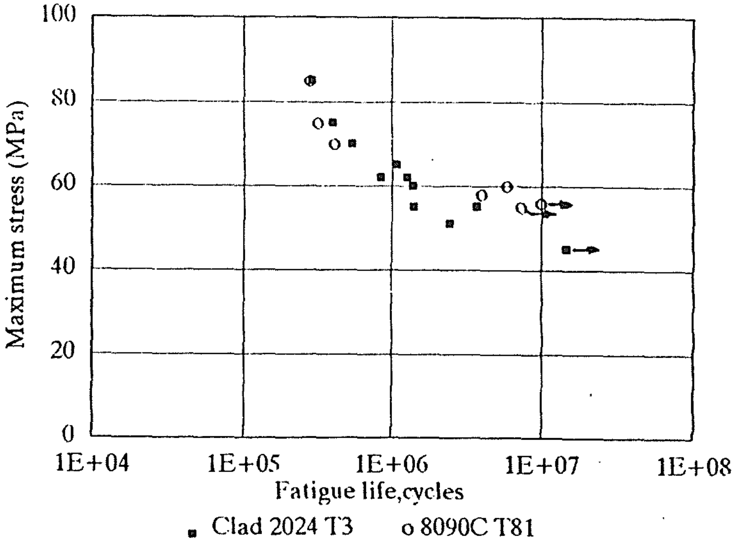


Figure 10. Engineering properties: Density.



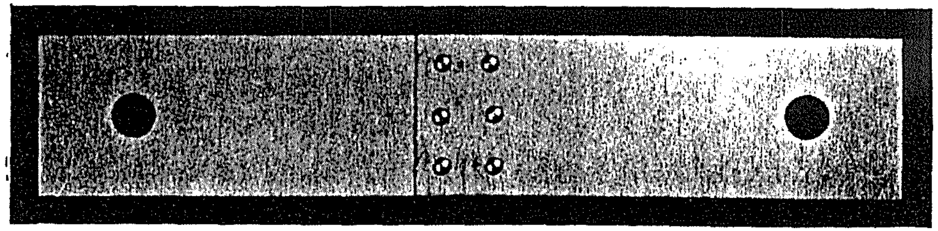


Figure 11. Fatigue properties. S-N curve of a rivetted joint specimen. (Comparison with clad 2024-T3) R = 0.1.

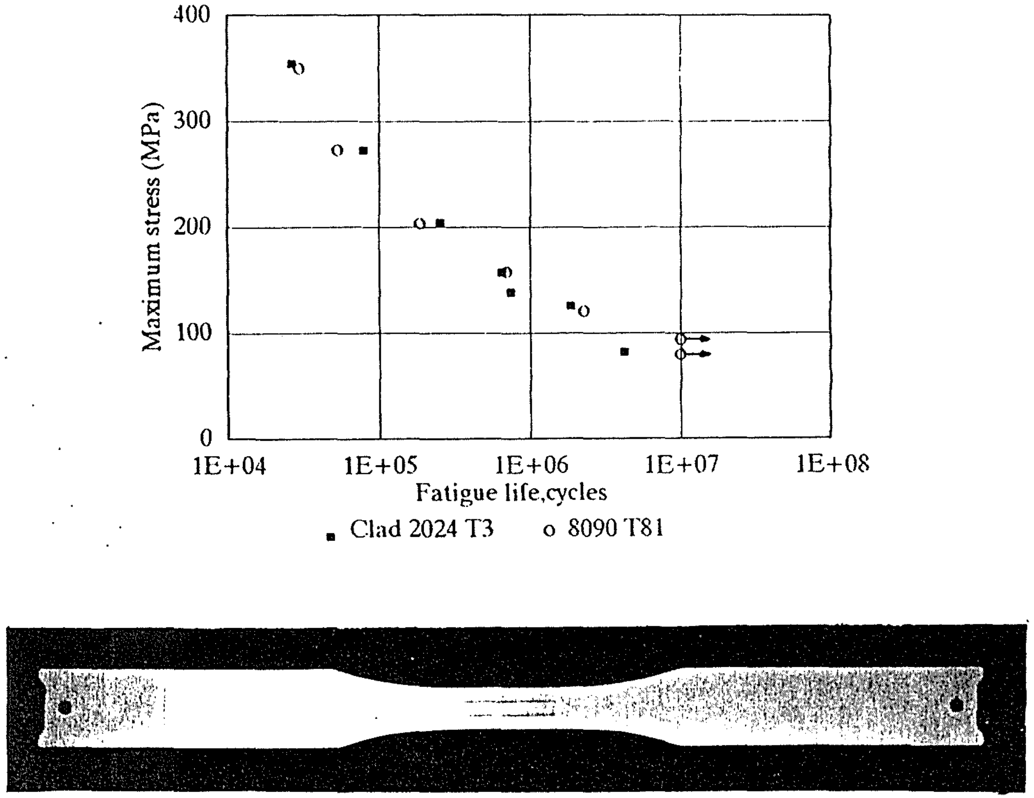


Figure 12. Fatigue properties in a corrosive environment. The specimen was primed and scratched in the L direction. R = 0.1.

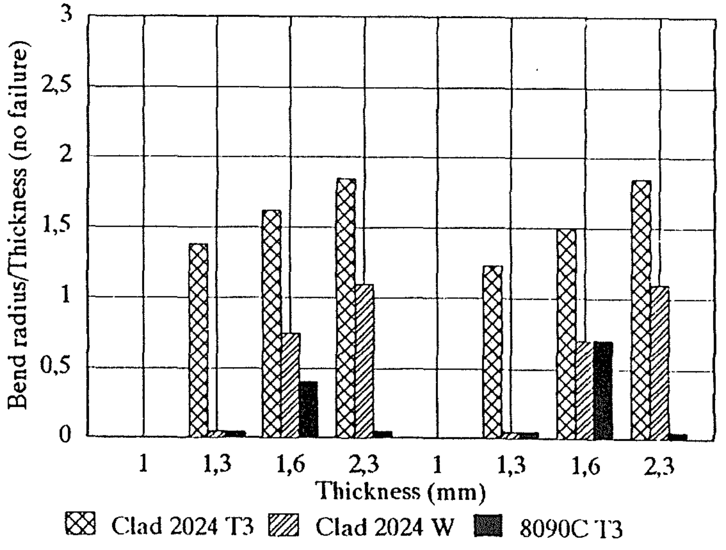


Figure 13. Bend tests for three thicknesses in L and T direction.

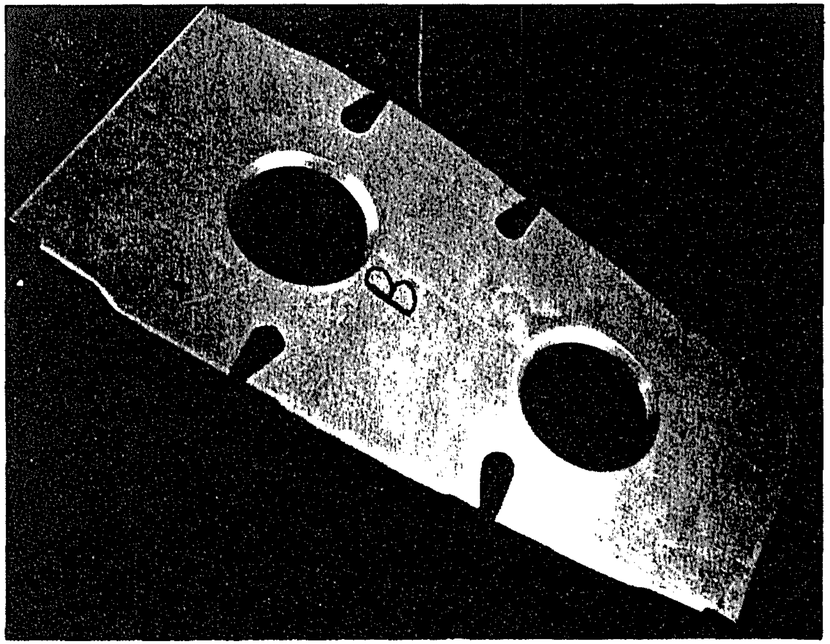


Figure 14. Typical structural detail part. (Rib 0.64 mm thickness). Formed in 8090C-T3.

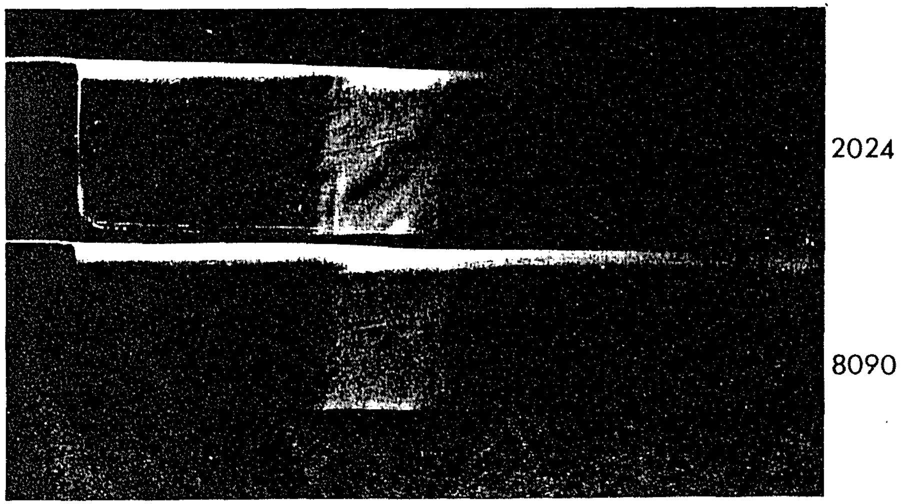


Figure 15. Detail of formed part comparing the compression flange waviness in 2024W whereas this is absent in 8090C-T3.

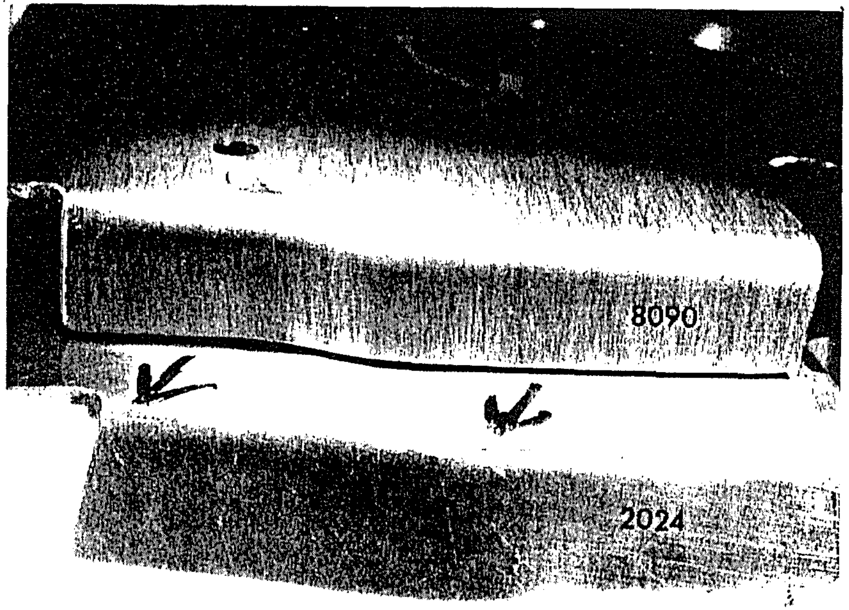


Figure 16. Detail of formed part in 2.3 mm thick sheet. Forming crack appears in 2024-W.

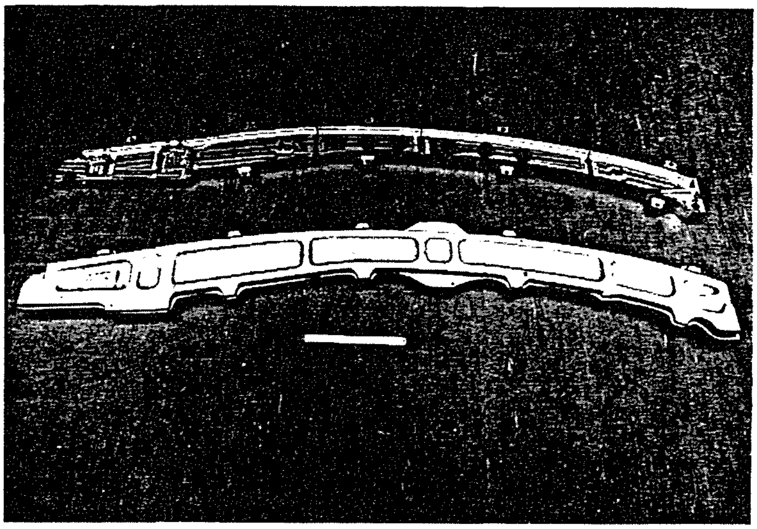


Figure 17. Typical 8090-T852 cold compressed die forgings for EH101 main cabin frame, before and after machining.

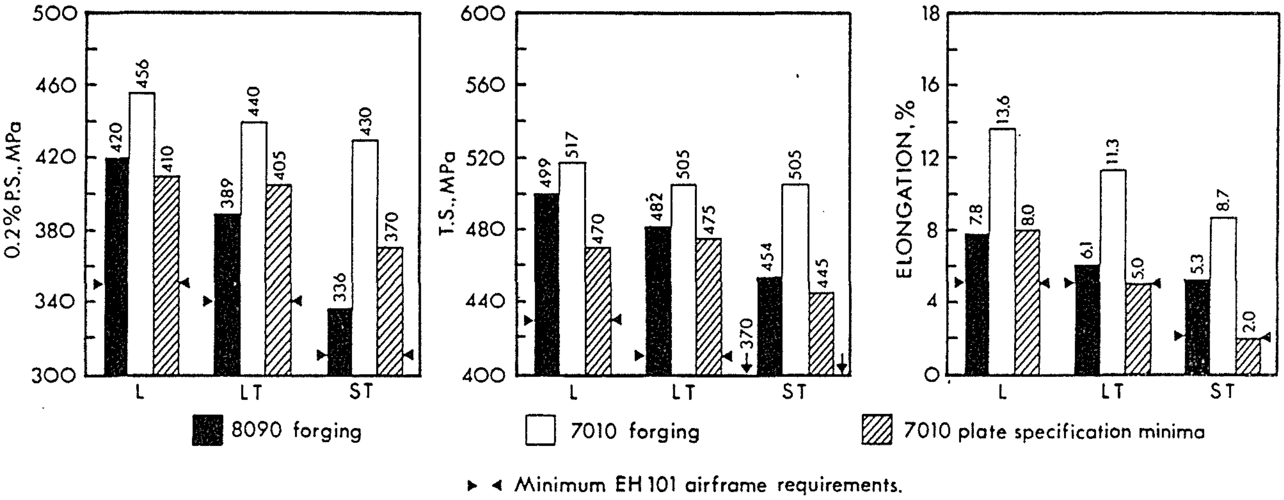
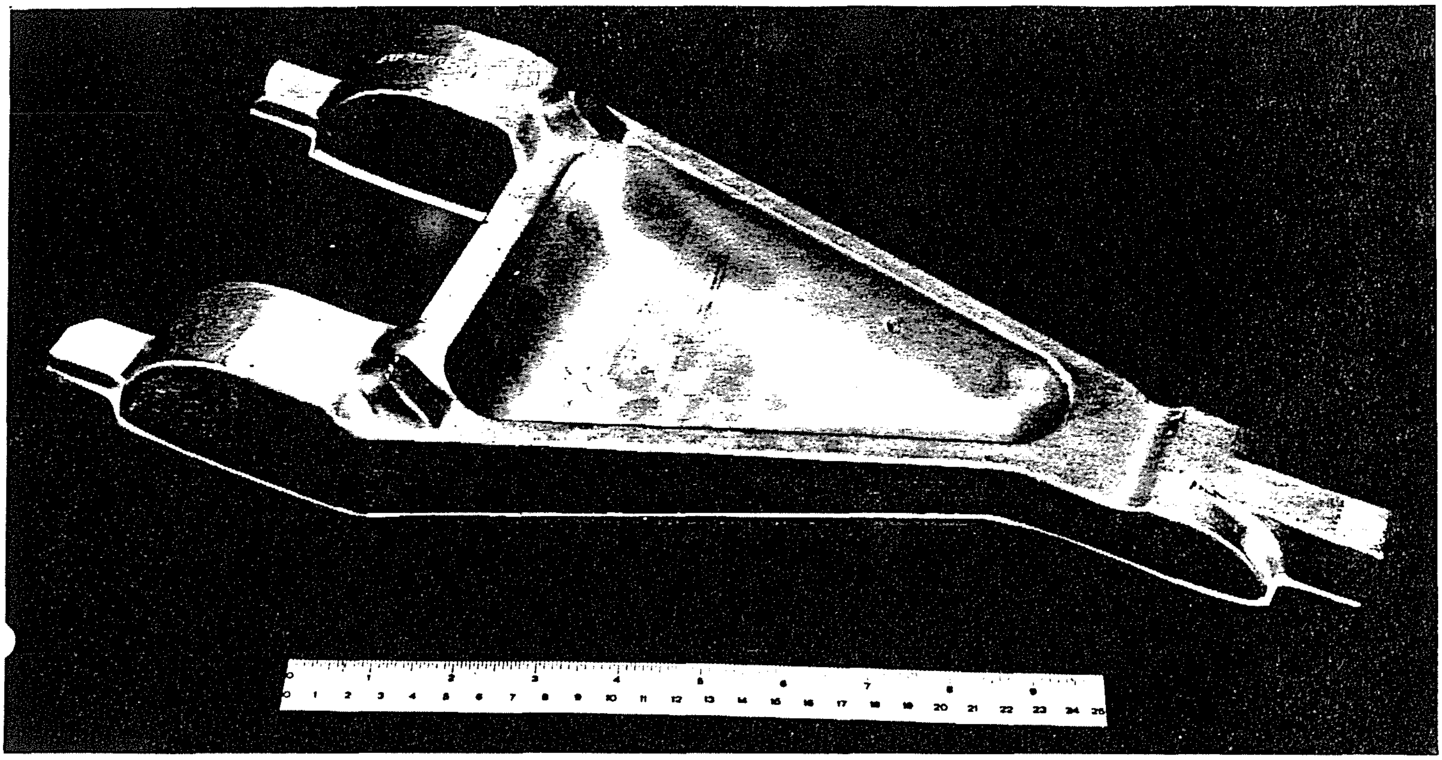


Figure 18. Comparison of mean static properties for trial 8090 and 7010 die forgings for EH101 main cabin frame compared to 7010 plate specification minimums to DTD 5130A.



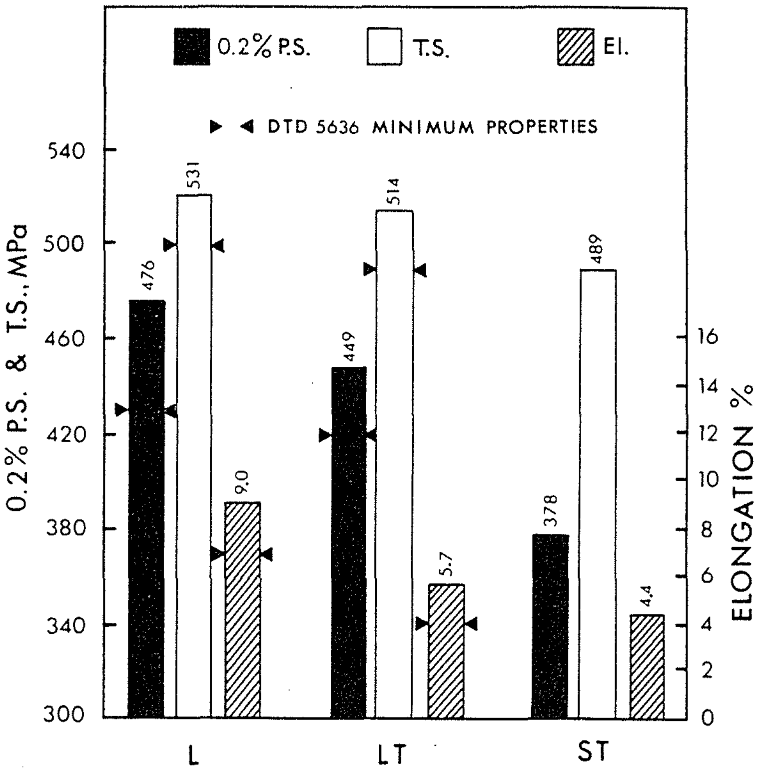


Figure 21. Mean static properties of a trial EH101 landing gear torque link in Al-905XL.

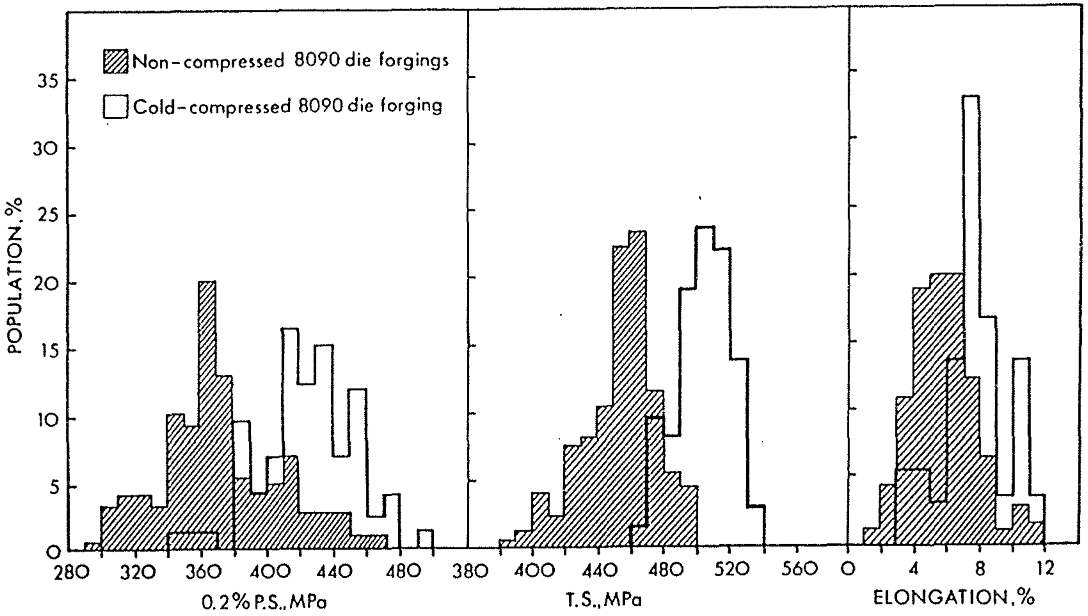


Figure 19. Comparison of static properties, cold compressed and non-cold compressed 8090 die forgings.

Figure 20. Trial EH101 nose landing gear cylinder in alloy Al-905XL