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TITLE: **LOW WEIGHT VEHICLE PROPERTIES OF ALUMINIUM ALLOYS FOR BODY STRUCTURES - PABS -**

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3.ABSTRACT

Knowledge of aluminium alloys is recent and limited in comparison with steel know-how. Collection of existing data has identified actual possibilities and has selected appropriate alloys for sheet materials, cast parts and extruded profiles. Evaluation of physical and mechanical characteristics of the aluminium alloys with indication of their mechanical and thermal properties have given the engineering choices. A review of shaping processes such as deep drawing, bake hardening, casting, bending, welding, have determinate better metallurgical capabilities and define the precise process conditions to be chosen. Representative specimens have been tested in simulated conditions for stiffness, fatigue, impact... for estimation of the service life behaviour of assembled structural parts. Conventional procedure tests have been performed on several high strength aluminium alloys after simulative process conditions in order to determine the levels of mechanical properties such as tensile, stiffness, impact and fatigue strength. These determinations allowed to quantify the possibility of weight reduction such as 40% using 120Mpa fatigue strength aluminium alloys (A 356 for instance) for body panels. This precompetitive work has-established a guideline in the choice of materials and specification for design of vehicle and has supplied data information in forming processes for manufacturing of vehicle.
This Project is part of the Low Weight Vehicle Prograrnme and is therefore complementary to the other 3 Projects: “Surface Treatment and Corrosion of Aluminium Alloy Body Structures” (SCABS), “Design of Aluminium Alloy Body Structures” (DABS) and “Manufacturing Aspects of Aluminium Alloy Body Structures” (hIABS).

4. INTRODUCTION

The properties of aluminium alloys have been determined for optimum design and service life of car body. Appropriate aluminium alloys have been selected for metallurgical compatibility with transformation processes. Manufacturing processes possibilities have also been optimised for high cadence production. Work has been performed on 4 main activities.

1) General properties and behaviour of selected alurninium alloys have been determined in terms of fatigue Iimit, high strain rate smength, long term aging behaviour, reusability of a.luminium according to different separation scenarios. Process parameters of joining techniques such as Resistance Spot Welding, Arc Welding, Laser, Adhesive bonding have been optimised in terms of resistance, ductility and fatigue strength of joined specimens.

2) Sheet materials forming processes have been checked in terms of alloys formability, surface texture isotropy and roughness, lubricant viscosity efficiency against galling, tooling material and mounting rules. Forming process parameters have also been ruled towards dimensional accuracy of formed component. Hardenability evoIution versus prestraining and post welding has been certified. New shredder alloy produced by aluminium reuse has been qualified by parts production.

3) Cast parts produced by advanced casting processes such as Vacuum Pressure Die Casting, Semi Solid Moulding, Indirect Squeeze Casting have been characterized in terms of tensile, impact, fatigue strength. Aluminium Matrix Composites properties according to different formulation and production potentiality by Squeeze Casting has aIso been investigated. Mechanical properties of Advanced Casted, cast forged and forged parts properties have also been compared.

4) Extruded profiIes hoHow section properties, homogeneity versus run off length and wall thickness, orientation and location testing have been assessed. Alloy selection and heat treatment condition are to be specified taking into account further manufacturing processes scheme such as forming, baking and further service life such as temperature exposure, dynamic strength, fatigue resistance versus damage sensitivity.

The vaIue of mechanical properties of aluminium aIIoys Ieads to the conclusion that aIuminium can be technically used for correct designing, processing compatibility and satisfactory service life of car body structures with 40% of weight saving compared to steel structures. Nevertheless Aluminium application requires a technological jump for industrialisation demanding very appropriate materials specifications, very accurate process parameter adjustments with more careful tooIing compared to steel. Anyhow alurninium use is possible to be ruled by conventional production technologies well and better suited for mass production than those used by plastic materiaIs. Economic rentability of aluminium material and processing overcosts is to be checked by mechanical components adaptation, save weight perception on fuel efficiency by customer and legal rules on fuel or emissions quantity.

5. TECHNICAL DESCRIPTION

General Behaviour and Joining properties

General description (Daimler-Benz)

Until now, aluminium in general, has been limited to specific light weight applications such as aeronautical products, which were not so cost sensitive and produced by small scale manufacturing techniques.
The aim of this Project was to identify the aluminium alloys that exhibit the best characteristics for automotive performance and have good compatibility with large scale manufacturing processes. The main objective was to find a database of mechanical properties for aHoys, semi-finished products and joinings suitable for automotive application.

Development of a Database Software (Alusuisse)

A database of aluminium data for applications in automotive is developed. It identifies actual possibilities and helps to select appropriate alloys for sheet materials, cast parts and extruded profiles. Evaluation of chemical composition, physical and mechanical characteristics of aluminium alloys is possible. Furthermore, values for bake hardening and fatigue properties are available. The database takes into consideration the aluminium data of different companies.
Thedatabase is implemented with the PC databank package MS Access. For graphical output, the software MS Excel is used. To run the application, Microsoft Widows 3.1 is required.

Recycling of aluminium body-in-white (Alcan)

This task was undertaken to assess the strategies for recycling the different aluminium alloys, in the various body architectures proposed, for the all aluminium body-in-white. Recycling strategies include various degrees of dismantling of the body from complete shredding without dismantling up to complete separation of the different alloy components.

Weldability Optimisation (Rover by TWI)

A comprehensive weldability optimisation review was earned out which covered aspects of materials such as alloy types, features, product forms, mechanical properties, defects, corrosion and protection and surface treatment and also covered processes available for joining aluminium alloys eg resistance, laser, arc, ultrasonic spot, friction, cold pressure, magnetically impelled arc butt, percussion and electron beam welding. This lead to a recognition of where knowledge was lacking enabling the development of the programme to cover selected work in the areas of laser, resistance spot and arc welding.

Characterization and properties after joining (Pechiney)

SeveraI material combinations based on sheets (5182, 6016), profiles (6060, 6082) and cast parts (Al Si7Mg0.3, A1-Si 10MgO.3) were selected with all the partners involved In PABS joining activities. Four joining processes were performed such as: Arc welding, Resist&ce s~ot welding, Clinching and Adhesive bonding.
The joining material behaviour was tesred with an <u>as delivered surface</u> (i.e. wi~hout any surface oxide removal) with two kinds of trials:
-static tests to evaluate the ultimate failure load or strength of the joint,

-dynamic tests so as to get a Wolher curve and the fatigue limit at 106 cycles.
All the specimen geometries and the laboratory procedures for joining were clearly defined with the partners.

Resistance spot welding & adhesive bonding (Renault by TWI)

The work carried out has covered three areas:

Resistance sDot welding

The initial study performed to generate weldability lobes used standard electrodes (truncated cone, Cu-Cr-Zr) and a DC power supply on as-received materials. The preliminary results indicated a small weidability range and high indentation of the sheets. Further trials were conducted to examine the following issues:
* Effect of power supply type (DC/AC}.
* Effect of electrode shape/materials.
*Effect of as-received versus surface treated materials.
The samples produced were assessed by tensile shear tests and samples made at the optimum condition have been fatigue tested.

Adhesive bonding

Six aluminium alloy profile to sheet material configurations comparing two surface conditions (as-received and oil spraying) using a one-part adhesive epoxy adhesive were evaluated. Tensile shear tests have been performed on samples in the as-bonded condition and after ageing treatment (3 weeks at 70° C, 2 hours at -20” C in humid conditions).

Weldbonding

Limited tests have been performed on a number of profile to sheet material configurations to develop suitable procedures for spot welding through an epoxy adhesive layer at the interface. Although adequate conditions could be achieved, work was not performed to optimise the weIdbonding procedures on aIl the material configurations. Limited samples have been produced for fatigue testing to compare the performance with resistance spot welding.

Joining properties (Opel)

The most important joining technologies for the aluminium application within the automotive industry were investigated in the PABS Project. Adhesive bonding, chching, riveting, ‘welding or com-binations of these techniques were evaluated and compared concerning mechanical properties, production ability and economical aspects. The tests were performed with different materials (sheet, profile, cast) and various sample cross sections.

Sheet properties

New shredder alloy (Alusuisse)

The re-utilisation of the mixture of various Al alloys used in a car body structure in the form of an Al sheet alloy for automotive applicatiofis wouId allow optimum vaIorisation of the Al body in end-of-life vehicles. Based on a reasonable assumption for a futu~e space frame design, different <model> alloys resuiting from a mixture of structural AI alloys typically proposed for space frame constructions have been evaluated. A full plant-scale test has been carried out with the most interesting variant.

Physic Characteristics (FIAT)

The main objectives of FIAT in this task were:
- assessment of physical and mechanical behaviour of aluminium specimens bonded and laser-welded
- evaluation of mechanical properties of welded cast/sheet specimens in relationship with the metallurgical status.

The chosen alloy grades were: 6016, 6111, sheet 5182 EDT and MF, sheet 5754 MT, with two different thickness: 1.2 and 2.0 mm.
The used adhesives were: two epoxy based (Ciba XB 5315 and Hexcel) and a polyurethane one (Gurit 7400).
A $C0_2$ laser was used with 5 kW of power.

Optimization of draw bead restraining forces (Volvo by SIMR)

The present work was devoted to an experimental and theoretical study of how geometrical- and material - parameters affect the restraining force in a draw bead. The experimental part was performed in a specially designed die set with computerized data acquisition and control. The theoretical part comprised finite element simulations and fitting of an analytical model from the literature.

Dimensional accuracy (Volvo by SIMR)

This investigation was focused on the spnngback of double-curved panels, The working hypothesis was that the springback is lowered by increasing the blank holding force (restraining force). The sheet materials used in the study were: steel (FeP06, 0.8 mm), 5182-O-EDT (1.2 mm & 2.0 mm), 6016 -T4-EDT (1.2 mm, 2.0 mm), and 611 l-T4-V65S-H90 (1.2 mm &, 2.0 mm).
.An analytical model was constructed and experiments, in which the binder force was varied, were conducted to study the springback of panels pressed with two different double-curved punches. After the pressing, each paneI was trimmed. The shape of the trimmed paneI was then measured in a coordinate-measuring device. The deviation from the shape of the punch, with which the panel was pressed, was, finally, determined.

Bake Hardening (Alusuisse & A1can)

The influence of post-shaping heat treatments on al body materials was established with specific attention to the compatibility with industrially applied paint bake and adhesive curing processes.
The non-age hardenable sheet alIoys AA5754 and AA5 182 suffer a decrease in strength at annealing temperatures > 150°C. For the two extrusion alloys AA6060 and AA6082, a strength decrease is observed at temperatures > 190”C.

Fatigue properties of pressed sheet (Alcan &Volvo by SIMR)

This task is to develop and verify methods to accurately predict the fatigue life of pressed sheet components specifically at hoIes and coinings. Mainly four aIIoys were examined: 5754-O, 5182-O, 601 6-T4 and 6111 -T4. The design concept suggested is founded on the local strain concept and requires input data form in form basic fatigue life data for smooth specimens, linear elastic stress concentration factors and a nominal elastic strain-time history.

Casting properties

Castability (Renault& Volvo)

The objective is to define the cast node impact test and fatigue test behaviors
Three alloys were essentially investigated: AlSi9Cu3 as secondary alloy, A1Si7Mg0,3 as primary alloy and 6061 recyclable alloy.
Alloys were as-cast, T4 and T6 heat treated. Nodes were tasted using 3 processes
- VPDC (vacuum pressure die casting)
- S SM (Semi Solid Moulding or thixocasting) both techniques using metallic core.
- ISC (Indirect Squeeze Casting) technique using sand core

Cast nodes thickness was from 3 to 3,5 mm. For impact test behaviour a vertical pendulum with a 3,386 kg weight was used. The full height of the weight to create the specimens machined from the cast nodes was needed to obtain rupture.

Initial properties of AMC by squeeze casting (Alures)

Various kind of Aluminium Mam'x Corrrosites (AMCS) have been produced with the Indirect Squeeze Casting (ISC) techno logy. The production process, the chemical compositions and the minimum thickness obtainable with this process have been optimized.

Near net shape parts properties (AMAG)

Indirect squeeze casting was selected as the most promising forming process. Casting trials were executed by indirect squeeze casting of a conventional AlSi7 Mg alloy, the same one with reduced Fe-content and a wrought AlSiMg0,5 alloy. The squeeze casting die for a node was designed, ordered and modified. Pressure die castings of the AlSi7Cu3 alloy and forgings of the A1SiMg0,5 were produced for comparison. Tensile tests were executed to compare the mechanical properties. The microstructure was described by metallographic methods. The anodising of squeeze cast nodes of AlSiMg0,5 was tested as well as welding.

Profile properties

Initial"and dynamic properties (Hydro Aluminium)

To determine the physico-chemical characteristics & mechanical properties for further utilisation of profiles in forming processes and for estimating service life. Alloys considered are EIydro 6060.85 and AMAG 6082.2 in the tempers T1, T5 and T7. Alloy suitable for easy recirculation and representing 1) a high ductile and 2) a high strenght alternative.
To provide data on strain rate sensitivity for a better understanding of the behaviour of an extruded profile under lateral and axial impact.

Extrusion forming properties (AMAG)

Specific heats of the alloy AA 6082, i.e. AISiMg 1 and 14 different tools for the test profiles were prepared. Extrusion trials were executed aiming for the fastest cooling rate at the press while maintaining the dimensional accuracy according to DIN 1748. Sections of the profiles were tested in different heat treatment conditions: T1 = as extruded; Tls = stabilised; T5 = artificially aged; T5b = T5 plus simulated paint baking heat treatment; T1 $x, T5$x, T5b$x = strained in Tls condition by approximately x%;

Flow curves of true stress versus true strain were produced to describe the plastic formability and its scatter. Stretch bending experiments were executed with profile #l, around a tool of 200mm radius. The scatter of the eIastic bending limits was determined by 3 point bend tests of sections of profile #+3.3.

Constant amplitude Fatigue (Volvo)

The main objective of this task was to determine basic fatigue data for two extruded aluminium alloys , AA6060 (AlMgSi0,5) and AA6082 (AIMgSi 1) by means of load controlled 4-point bending and strain controlled fatigue tests (LCF) and to predict the fatigue life of a hollow extruded aluminium profile.

Random load fatigue (Renault)

The aim of this study is to evaluate the potential of severaI fatigue life models to predict the fatigue behaviour of notched aluminium profiles under random loading.

Load controlled fatigue test were conducted using 4 points bending on hollow square profiles.

The fatigue tests were performed on 6060 end 6082 profiles wiht a hole of 6mm in diameter (ref. RC)D 5 106). The random fatigue tests were performed with the RENO_B spectrum consisting of 440 data points. The fatigue life was defined as a 109?o stiffness 10ss of the specimen.

The results obtained on the two different alloys showed almost no differences in term of fatigue life. The analysis was only performed on the 6060 alloy results where results on constant amplitude fatigue where available from task 4.3.

A PC based software was written to evaluate the different fatigue life predictions models. Constant amplitude fatigue data from Volvo (task 4.3) were used as input for the analysis. Elastic as well as elasto-plastic analysis was performed on the results from the 6060 serie alloy.

6. RESULTS ‘

GeneraI behaviour and Joining properties

Data collection and requirement study (Daimler-13enz)

During the PAIRS Project, the whole range of aluminium products such as sheets, profiles and casting have been investigated and characterized. A high amount of data are now available to select alloys, semi finished products, heat treatments, parameters for manufacturing techniques and joining technologies. AIusuisse has established an easy possibility to store all the obtained parent material data in a way suitable to be used by designers and processing engineers.

Properties of basic materials

Various basic material data such as static and fatigue strength of delivered material, after deformation and heat treatment and after life cycle aging as well as strain rate sensivity and fracture toughness have been detemnined.

Development of a Database Software {Alusttkse)

The basis of the database is a list of alloys together with general information about their properties and applications. The main part of the database is subdivided in the folIowing five menus:

. chemicaI composition
. physical properties
. mechanical properties
. bake hardening
. fatigue properties

The data depend on various parameters such as source (company), productform, dimension, temperature, temper etc... Graphical displays of typical cases of mechanical and fatigue properties are included.

The database consis[s of two applications, PABS-query for query and PA BS-data for data manipulation. The data of the database is stored in a single file and can be administrated centrally. Updates of this datafile can be sent periodically to the users.

Data has been coHected and entered for the aHoys EN AW 6016,6060 and 6082. during the Project, the authors obtained data from different companies. The database is partially filled with this data to demonstrate the functionality. The authors refuse the responsibility for the correctness of the data.

Recyclability study (A1can)

From computer simulations of the aluminium alloy compositions and forms which are proposed for the body-in-white of various architectures, from the extruded spaceframe with cast nodes to the stamped sheet monocoque, the following conclusions have been reached:

AH of the aluminium in all architectures is recyclable, but to recycle or re-use iri a closed loop back into the original alloys and forms varies with the architecture and separation strategy.

Complete shredding, without separation of the alloys and components, aIIows re-use of between 33% and 44% of the material in the original forms for all architectures, except the spaceframe without castings, 8170 of which can be re-used in this way.

With partial separation, the re-use fraction of the former architectures above can be increased to 65% to 779’0.
With extensive separation, all architectures can be almost fully re-used back to the original alloys and forms

WeIdabiIity optimization (Rover by TWI)

A state of the art optimisation study was achieved on the joining of aluminium aHoys which included topics such as joining process description, equipment, consumables, joint designs, thickness capability, joint properties, design tolerances and imperfections. Assessment of this information enabled key areas of unknown information, regarded as being pertinent to the automotive industry, to be recognised and be investigated within the PABS programme. These included:

Laser welding
Weld appearance, porosity levels and weld strengths were determined for COZ and Nd:YAG laser welding alloy 6060.
The effect of simulated paint stoving and adhesive curing treatments on tensile strength performance was determined for C02 and Nd:YAG laser welds.
An optimised joint section thickr~ss was established for 2kW I’Jd:YAG welding, along with tolerance to fit up for lap and butt joints.
Maximum beam/joint misalignment tolerance and focus tolerance were also determined.

Resistance SQot welding
A relationship between fit up, initial gap and the force required to bring parts into contact was demonstrated against the ability to produce good welds.
Evaluation of current power supply and power usage for alternating and direct current equipment revea~ed different power consumption.
The choice of power supply was shown to influence the welding of alloy 5754 in terms of sticking and splash.
An evaluation of the effect of a scratch brushed surface versus as-recieved surface revealed different effects between the welding range of 5754 alloy than with 6016.

Arc Welding
An optimised wel.ding speed was established for synergic MIG Iap joints on alloy combinations of 6060/6060 profiles and 6060/AS7G, 6060/AS 10G profile/castings.
Filler wire diameters were optimised against 1.2 and 2.Omm materials for carrying out Synergic MIG lap and butt joints, and TIG lap joints.
Surface contamination was shown to have an affect on weld quality.
Weld strengths were determined for MIG and TIG welded butt joints and MIG welded lap joints and compared to parent material strength.

Welding Properties (Pechirtey)

The main results are given for each technique.

Arc welding
The development of a new generation of MIG pulsed equipments allows now the welding of thin aluminium products up to 1.2 mm. The gap between the parts to be joined can be up to the thickness of the thinnest material.
The typical static properties obtained with MIG technique and 4043 filler metal are influenced by the material properties. On 2 mm thick materials and on butt welds the UTS increases from 163 MPa for 6060/5182 to 222 MPa for 6082/5182. For cast parts the same evolution is observed for butt welds as well for fil}et welds.
The fatigue behaviour on cross specimens with 4 beads is the same for all the material configurations tested. The fatigue limit measured for ASG/6000 and 5182/6000 configurations is close to 50 MPa at 106 cycles with a 20 MPa scatter band.

Resistance SRot Welding

The material weldability was evaluated cm a single phase AC pedestal machine with a truncated cone eIectrode CuCrZr and two sizes of tip diameter: @5.5 mm r 60 mm fort el.5mmand 08mrnr80mm fort >1.5 mm.
The static results depend on the welding parameters and consequently on the nugget quality and diameter. With a weldability range higher than 2000 Amperes and considering an average nugget diameter of about 54 t, the shear failure load is higher than 350 daN for 518201.2 mm sheets. In this case the welding current was 22 kA and 300 daN for the welding force.
The electrode tip life is higher than 1000 spot welds without any cleaning *or* machining and welding current incrementation.
The fatigue behaviour is correct with a fatigue limit for sheet configuration near 30% of the ultimate static failure load of the weld.

Clinching
The trials were carried out with the stitch process using tools supplied by Homax (Bolloff - Attexor) and we used a 4 part die with a 7 mm nominal diameter (R7 4P).
The static properties of the joint depend on the material thickness and on the material properties. An increase of the material thickness from 1.2 to 2 mm improves the shear failure load &m) by about 50%. (Fm = 2200 daN for 1.2 mm and Fm = 3500 daN for 2 mm).
The higher failure load is obtained with the highest strength resistance material positioned on the punch side (5754 1.2 mm Fm = 184 daN and 60821.2 mm T5 Fm = 253 daN).
The fatigue results seem to be a little bit better than the resistance spot welding ones.

Adhesive bonding
Joining had been carried out on oily surfaces with Ciba-Giegy one part epoxy adhesive XB 5315.
The static resistance of the joint is not directly dependent on the alloy but related to the stiffness of the material. Thus thicker material gives better resistance. There is no improvement of the joint properties by the presence of weld spots.The loss of the lap shear failure load after four week moist cataplasm ageing can be up to 40 % .
The fatigue behaviour of adhesive bonding and welbonding joints is significantly better than for the spot welded and clinched joints. The fatigue Iimits for all configurations are similar, close to 7 kh^{T} compared to 2 khl for spot welded joints.

Resistance spot welding and Adhesive bonding (Renault by TWI)

Resistance suet welding
Following the initia~ trials, an optimisation study was performed using a domed eIectrode (11 mm diameter, 100mm radius), instead of the truncated cone electrode. This alteration reduced the amount of indentation and increased the weldability range but at the expense of a higher current level. An electrode life without adjusting the current level of approximately 350 welds has been obtained with a domed electrode (Cu-Cr-Zr),.The main results achieved to examine the questions of power supply type, electrode materkd and as-received versus surface treated materials are summarised below.

* An AC power supply gave Iess sticking and more consistent results and al$o reduced the influence of the Pe]tier effect which causes damage to the electrode surface for a configuration involving 6000 series profile to 5000 series sheet.

* A Cu-Zr electrode with DC power supply, for 6000 series to 6000 series combinations, gave a good compromise between:
  - level of current used;

- width of the weldability range;
- quality of the spot welds (less splashing and sticking);
- consistency of results.

* Surface Deatment of the material introduced an improvement in:
    - weld quality;
    - weldability range;
    - visual appearance;
    - reduced sticking.

However, these advantages have to be balanced against a higher current level and practicality of surface treatment in mass production.
The tensile shear properties of the resistance spot weld depended mainly on the nugget diameter, and not on the method of producing the weld.

<u>Adhesive bonding</u>
The results of the static shear tests on the epoxy adhesively bonded profile to sheet configurations showed that it was possible to achieve a consistent level of strength. The follwing points were also noted :

* 6082 (1.2mm) / 5182 (1 .2mm) profile to sheet combinations had the highest lap shear strength but was more sensitive to the moist cataplasm treatment.
* The oil spraying on the sheets did not have a significant effect on the initial lap shear failure loads.
* After three weeks moist cataplasrn treatment, joints made with the as-recieved adherends suffered less than 10% loss in static shear strength.
* After three weeks moist catap]asm treatment, joints made with oil spraying suffered less than 20% loss in strength but with a change in failure mode (cohesive failure to adhesive failure].

Weld characterization and properties of joinings (Daimler-Benz)
A base of test data is now available to evaluate joining technologies, their applicability and the influence of surface conditions and temperature together with humidity. Data for design departments as well as processing departments have been obtained.

Finite element analysis of resistance spot welding (Daimler-Benz)
FEM crack tip elements were used to simulate resistance spot weldments of peel and shear type load on different sheet thicknesses. An excellent correlation between two different sheet thicknesses was found by calculating the local stress intensity via J-Integral. A good correlation was found between peel and shear type specimens as well. Summarizing the results it is possible to reduce the amount of specimens to be tested dramatically to one material configurations because all other configurations can be calculated.

Joining properties (Opel)
The Project was organised to find out fundamental knowledge for the aluminium application in automotive industry. The investigation of the joining techniques allow the section of the most possible application for alurninium structures under consideration of static and fatigue requirements, production time or costs. The influence of the used aluminium alloy, the material thickness and the variation of test parameters have to be considered by the evaluation of the achieved test results.

Sheet properties

New shredder alloy (Alusuisse)

Compared to standard Al car body sheet alloys, the <shredder> alloy shows:
comparable forming behaviour
similar strength level
comparable assembly performance
and only slightly reduced corrosion resistance

Physic Characteristics (FIAT)

The main results are summarised in the following items:
The quality of laser-welded specimen is affected by the aluminium alloy grade.
The static behaviour of laser-welded specimen varied from the 53% to the 90% of the base material.
Higher dilution ratio have been measured in Iaser welded joints (0.87) and TIG joints (0.83); lower value (0.63) in MIG joints.
The heavy oxide layer on cast material causes serious problems in the arc welding process if stepped specimens are used. Butt joint welds can be obtained.
The TIG welding processing induces an heating effect on joined parts that affect the material up to 30 mm away from the weld (3 mm parts welded).
Filler material permit the welding on completely locked specimens in the fixtunng tool.
Temperature up to 100 C can be reached on the weIded part during the process.
The analysis on adhesive bonded joints confirm the experimental data obtained during the experimental activity in Sub-task 2.2: shear resistance up to 23 MPa are reachable with CIBA XB 5315, chosen like better adhesive for our applications.

Forming properties (Renault by CRM)

Compared to deep drawing steels, aluminium alloys exibit a comparable ductility, a lower anisotropy coefficient and a higher hardening rate. The strength level is comparable to DDQ and ULC-Ti steels for series 5000 while alloy AC120 is slightly less resistant.

The balance between the strength in different forming paths is different from that of steel, resulting in the need to adapt the press tooIs specifically for aluminium (die and punch radii, . ..). Also, strain hardening in equibiaxial tension is very low, so that uneven distribution of strains is observed at a local scale on stretched parts. On the contrary, in complex strain paths [stretching of deep drawing followed by uniaxial tension), some strain hardening remains as well as non negligeable residual ductility. This feature is favourabIe for multistep stamping, for which aluminiurn should have some advantage on steel.

As far as springback behaviour is concerned, three cases can be considered. Firstly, in 90°bending on a punch blankholder and die set, analytical formulae developed for steel can be used with only minute modifications and give enough accuracy for most practical problems. Secondly, in the forming of U channels, a large scatter of the springback is observed, due to unsymmetrical and unstable forming of both sides of the U. The reason is the poor control of material flow in the tooling, due to a low friction coefficient generated by the low surface roughness of the aluminium sheets. Thirdly, in V-die bending, a single set of die opening and punch radius can be found that ensures a good shape accuracy for a large range of alloy properties and sheet thicknesses.

For the sheet thicknesses used in practice, wrinkling is probably not the most critical defect on aluminium sheets and could even be better under control by optimizing the frictional properties. Also, dent resistance is favorably influenced by the thickness and to a smaller extent by the mechanical resistance of the material.

Finally, the aspect after painting should not be too much impaired by the increase of roughness resulting from the metal deformation. A large range of strain paths and strain leveIs induce roughness well below the critical values above which this property will deteriorate. It should however be recalled that series 5000 alloys are non suitabIe for visible parts because of the formation of Liiders bands, even if outside these defects, the surface remains smoother than the one of 6000 series alloys.

Draw bead optimization (Volvo by SIMR)

The results can be used by the tool designer to design draw beads to a desired restraining force by direct use of the experimental data avaiIabIe in an EXCEL-database. Another approach is to use the analytical model, fitted to the experimental data, to obtain rough estimations of how the restmining force can be varied through the bead geometry, and/or through material parameters, The database and the analytical model can also be used to make die changes faster when the restraining force must be changed locally due to die wear, change of sheet materiaI etc.

Dimension accuracy (Volvo by SIMR)

Both the theoretical analysis and the experiments conducted show that:

the springback is <u>lowered</u> with increasing binder force (restraining force) level.

the material properties, the sheet thickness and the punch shape play a significant role, as far as the <u>minimisation</u> of springback is concerned.

Bake Hardening (Alwmisse & Alcan)

For the AA 6xxx sheet alloy, temperatures > 150°C are necessary to achieve the desired strength increase. The optimum age hardening temperature is approx. 200”C. Extended storage at room temperature does not impede the subsequent age hardening process.

The non-age hardenable sheet alloys AA5754 and AA5 182 suffer a decrease in strength at annealing temperatures > 150”C. For the two extrusion alloys AA6060 and AA6082, a strength decrease is observed at temperatures> 190”C.

The age hardenability of AIMgSi aIloys and the loss of cold-work induced strength in AIMg alloys during industrially applied paint btike and adhesive curing processes must be taken into account in the car body design. Optimum use of the strengthening mechanisms active in the AIMgSi system offer a significant downgauge potential for the body sheet structure (outer an inner body panels).

Fatigue properties of pressed sheet (A1can & Volvo by SIMR)

From the fatigue investigations of pressed aluminium sheet the following main conclusions can be drawn:

- the fatigue tests of smooth specimens indicate that no account of prestraining as obtained during forming is needed in the fatigue life analysis as long as the forming strains is lower than 0.1.5. The same seems to hold also for the peak ageing state of the 6000 series materials.
- in both the strain controlled testing of smooth specimens and the fatigue testing of pressed sheet specimens it was found that the fatigue strength rank in accordance with the tensile strength of the materials.
- finite element simulations incorporating both sheet forming and fatigue loading seem to be appropriate to establish the required stress concentration factors. The results of

both the forming conditions and the stress concentration during fatigue agree with experimental results.
- the fatigue life estimation procedure for pressed sheet components based on the Iocal strain approach turned out to work excellently; lives were generaIly predicted within a factor of two both under constant and variable amplitude loading.
- proper design of the transition from the pressing to the plane sheet has potential for improving the fatigue behaviour.

Casting properties

Castability (Volvo& Renault)

AlSi7Mg0.3 presents the best impact test behaviour for all heat treatment states (As-cast, T4 and T6). The Fe low content and absence of copper explain the best behaviour. The best results are obtained with the T4 states. The high ductility of AlSi7Mg0,3 is the main parameter of this good behaviour. Elongation from tensile test is confirmed by energy of impact fall height test. Fatigue life on specimen from 3 casting processes is also comparable in the range from 90 to 120Mpa.

Initial properties of AMC by Squeeze Casting (Alures)

High strenght alloys have been produced and tested to show the possibilities of this technology. Strenght above 400 MPa and thicknesses of 3-4 mm have been obtained; low elongations are still a mechanical limit of these materials. Welding and machining can be performed according to the particular procedures.

Near net shape parts properties (AMAG)

The production experience gained at the beginning of the Project concerning the two step casting/forging process suggested nearly as high production costs as for one step forging, but poorer mechanical properties. Therefore, indirect squeeze casting was selected to compare the mechanical properties of the selected node, for which forgings were available. Squeeze casting of the wrought alloy could be performed. Both the AlSi7Mg-type alloys and the AlSiMg0,5 alloy could be solution treated after squeeze casting. The AISiMg 0,5 samples in the as cast condition exhibit the highest ductility (A5 > 20%). The peak aged T6 casting alloy exceeds the strength of the squeeze cast AlSiMg0,5 T6 sampIes by about 50’% with elongation at rupture above 5%. Comparing the T6 conditions of the AlSiMg0,5 alloy, the forget version has about 259?0 higher strength values and as well better ductility than the squeeze cast one. The squeeze cast AlSiMg0,5 parts yield higher strength values and much higher elongation at rupture than the *pressure* die cast ones.
The squeeze cast AlSiMg0,5 parts could be anodised for decorative and protective purposes. In the as cast condition such parts could be cold deformed further. the weldability of the wrought alloy is maintained.

Profile properties

Initial and dynamic properties (Hydro Aluminium)

A programme to document the mechanical properties needed for design, manufacturing and life time considerations was designed:
1) Documentation of the variations in mechanical properties at room temperature over time needed for bending/forming considerations and life time estimates.

2) Documentation of the influence of elevated service temperature on the mechanical properties over the life time of a vehicle.
3] Extrusion anisotropy in hollow sections in order to allow for optimum bending and forming performance.
4) Uniformity of mechanical properties over the run-out length in order to document the uniformity of the profiles over the run-out length.
5) The combined bending and torsion @i-axial) fatigue testing in order to predict life time and optimize design of hollow sections prone to bending and torsion.

In order to secure reIevant data test equipment capable of testing samples representing the normal surface of the extruded profile as well as the normal variation in metallurgical structure were selected. Normal extruded profiles in HA 6060.85 and AMAG 6082.2 alloys were sectioned samples representing the wall as well as the comer were tested separately. A quarter of a symetric profile was tested as verification.

Extrusion forming properties (AMAG)

Exmsions of AA6060 alloy do not yield significantly higher strength levels by enhanced water cooling at the press, but the alloy AA6082 is very sensitive to the cooling rate. Profiles xl, #2, #3.2, #3.3, #?, #l 3, “KCl” and “BU˃’ could be cooled by water jets at the press still preserving the dimensional accuracy, whereas the others would be distorted and were only cooIed by air jets. The dimensional tolerance aIlowed by DIN 1748 cause considerable scatter in the elastic limit of the profile, the force needed for bending and the corresponding back spring angle,
The T1 condition of AA6082 produces a considerable natural ageing effect and reduces the artificial ageing efficiency. Therefore a stabilizing treatment Tls was introduced. The simulation of paint baking T5b does not change the mechanical properties achieved by the T5 condition. Some AA6082 profiles suffered by extreme grain growth in surface near regions. The strength level of the 6082 alloy depend on the extrusion conditions and therefore on the cross section and the cooling rate. The results can be grouped with $R_{P0,2}$ between 80 and 140 iMPa, R_{PO} ~$R_{\sim}$ around 0,5 and n-values of 0,22 to 0,31. The formability in the Tls condition’ is significantly higher ~han in T5 condition. After T5 ageing the high strength profiles of alloy 6082 reach different sbength levels R~ between 270 and 390 MPa.
Straining the AA6082-profiles in the TIs condition up to 10% yields almost the same R~ values after subsequent T5 ageing as the unstrained. Profile #l of AA6060/Tl and AA6082flls were successfully bent around a radius of 200 mm. The back spring angle of the stronger AA6082-profi1e increases faster during bending than that of AA6060.
The scatter of the onset of plastic deformation of profiles 3.3 amounts to A 7% in strain and stress for the AA6060/Tl profile and 13% for the AA 6082fll s-profile.

Constant amplitude fatigue (Volvo)

The fatigue limit of the notched profiles (AA6060-T5B) tested under load contro~led conditions in four-point bend was determined to 26 MPa. Strain cycle fatigue data together with monotonic flow curves and the cyclic stress amplitudes at half the fatigue life were established for samples with different combinations of prestraining, heat treatment, sample thickness, direction and alloy.

Random load fatigue (Renault)

Elastic analysis

The influence of the fatigue model used in the constant amplitude fmigue data w& assessed. 4 models were used: Basquin, Woehler, Stromeyer and Bastenaire. The analysis performed consited of a rainflow counting followed by a fatigue analysis according the model under study followed by a damage summation using Miner rule. All 4 models gave conservative life estimates. The best results were obtained with the

Basquin model. This is consistent with the representation of the constant amplitude fatigue data which was best represented by Basquin equation.

Elasto-Plastic analysis

Neuber as welI as GIinka modeIs were used to approximate the stresses and strains around the notch. Using the local values, 3 types of fatigue models were used for the fatigue analysis : Manson with Morrow comection, Smith Watson Topper and Seeger.
It was shown that this type of analysis gave a closer representation of the actual test resuIts compared to the elastic analysis. No differences were found between Neuber and Glinka approaches. Also, no differences were found in the 3 different fatigue models used in this analysis.

7. CONCLUSIONS

General behaviour and Joining properties

Data collection and requirement study (Dairnler-Benz)

Properties of basic materials : life time aging is not critical for 5xxx non heat treatable alloys. There is a tendancy to increase in static and fatigue strength properties with decreasing ductility, depending on the heat treatment was found in 6xxx sheet and profile alloys after paint baking and ageing simulation. The influence of the various strain rates is marginal compared to the influence of a temperature range between -30°C and +120°C. A rather high fracture toughness especiaHy perpendicular to the extrusion direction was found.

Development of a Database Software (Alusuisse)

The present software and report document the feasibility of an aluminium database for automotive applications. For a successfu} outcome of the Project, the database should now be tested and used by the companies and feedback should be given to the authors. More data should be collected and entered into the system. In a next step, the database could be extended to take into consideration further properties as joints, corrosion resistance, formability y etc... At last, suitable reports and query forms should be developed to allow an effective usage of the database.
In the next time, Alusuisse will maintain the software and carry out modifications and extensions by orders of the companies. As a first step, a workshop is proposed to introduce the users into the software (query and data input) and to stimulate further activities.

Weldability optimisation (Rover by TW1)

A programme of work has been earned out to investigate the processes available for joining aluminium alloys and to target areas of welding needs for the automotive industry concentrating on laser, resistance spot and arc welding. The data achieved has moved the industry's knowledge closer to achieving optimisation of joining aluminium.

Characterization and properties after joining (Pechiney)

Arc welding is possible on thin materials up to 1.2 mm with pulsed MIG equipment on as delivered materials and degreased surfaces.
Aluminium sheet and profile materials are resistance spot weldable on as delivered surfaces. The weldability range is higher than 2000 Amperes. The shear failure load of a 5~t nugget diameter for 5182 HO 1.2 mm is close to the value obtained on 0.8 mm steel sheets.
Clinching properties depend on material thickness and properties. An optimization of the clinching parameters is necessary in regard to the joint properties.
Adhesive bonding is possible on materials without any surface treatment and, on oily surfaces, the joint properties depend on the choice of the adhesive / oil couple. No improvement is observed for weld bonded joints.

Resistance spot welding and Adhesive bonding (Renault by TWI)

Resistance Spot Welding in as received condition is possible providing that attention is to be paid to the appropriate electrode shape, electrode material and power supply, but there is less tolerance in the process compared to etched surface.

Adhesive bonding showed also good possibility of combinations depending on assembling stiffness. But detailed evaluation of the fatigue performance of joints made on oily surfaces in particular in a moist environment is to be assessed.

Welds characterization and properties of joinings (Daimler-Benz)

In general, it is very difficult to compare different joining techniques due to different joint geometries and parent materials; In general, concerning static and fatigue behaviour all joinings with adhesive bonding are much better than other joinings where only a circular area is joined. Therefore, the combination of a “spot joining technique” (clinching, spot welding, riveting, etc...) is mostly recommended, also due to manufacturing advantages. Additionally it has to be taken into account that a smaller overlapping, when adhesive bonding, offers better strength resuIts even if another joining technique is added. The objective of further investigation could be to calculate the optimal joint geometry for adhesive bonding or combined joining techniques.

Finite element analysis of resistance spot welding (Daimler-Benz)

Iocal fatigue strength criteria have been proved to allow a correlation between different specimen geometries. Therefore this method can be used to reduce the number of specimen geometries in laboratory tests when optimizing the welding parameters or when studying new materials; Furthermore, the method can be used in a way to define quality criteria for weIdspots. The influence of variing geometries (spot diameter, spot eccentricity etc...) can be studied easily. In a long term approach, the method should be developed ti support the design of spot-welded car bodies. The global loads at a signle weld-spot (in terms of normal load, tangential load and torsional moment) from a fuH car body FEM-nlodel should be checked with a design envelope defined by local s~ength criteria. Therefore a correlation between the global load vector and the local strength criteria has to be evaIuated.

General use (Opel)

The results in general have shown that alurniniurn in Automotive structures can be used in different ways for simple components as weIl as complete body concepts taking into account transformation processes parameters and tooIing optimisation and using quasi comparable machine equipments as steel materials.

Sheet properties

New shredder alloy (Ahsuisse)

Aluminium car bodies can be recycled into a new sheet alloy for automotive applications provided appropriate measures are taken in design/alloy selection and recycling (dismantling/alloy sorting).

Forming properties (Renault by CRM)

Forming of aluminium sheets requires more care compared to steel sheet, but this work has enabled to quantify the possibilities of application to produce formed sheet panels. Moreover optimum rules to be managed concerning surface texture , lubricant, tooling materials and complex deformation paths have been assessed.

Optimization of draw bead restraining forces (Volvo by SIMR)

By changing the tool geometry the ratio between restmining stress and yield stress (DBRR) could be varied in wide ranges (from 0.2 to 0.9]. DBRR increases with increasing bead height and sheet thickness and with decreasing radii and clearance between the male and female parts.

A FEM-model of the experimental device was used to study basic deformation mechanisms in the bead. An ana~ytical model from the literature was also used to calculate the restraining force. A satisfactory agreement between experiments and calculations was obtained for both theoretical approaches

Springback properties of sheet aluminium in 3D-struct~res (Opel)

This study shows that the following relationships should be considered in the design stage:

$$\frac{R_{p1} \bullet \sigma_y}{EF_1} - \frac{t}{2} \quad \text{and} \quad \frac{R_{p2} \bullet \sigma_y}{EF_2} - \frac{t}{2}$$

In these expressions, R_{Pi} = minor punch radius, R_z = major punch radius, CJ_Y = yield strength of the sheet material, t = sheet thickness, $\sim F_1$ = an elastic factor along R_{pl}, and EFz = an elastic factor along $Z?_{P2}$. The lower the values of the expressions above are, the better it is, as far as the minimisation of the springback is concerned.

A proper punch design, or selecting another sheet material, or another sheet thickness together with a moderately high binder force helps, in order words, minimizing the spnngback.

Bake Hardening (Alusuisse & Alcan)

The age hardenability of AIMgSi alloys and the loss of cold-work induced strength in AIMg alloys during industrially applied paint bake and adhesive curing processes must be taken into account in the car body design. Optimum use of the strengthening mechanisms active in the AIMgSi system offer a significant downgauge potential for the body sheet structure (outer an inner body panek).

Fatigue properties of pressed sheet (Alcan &Volvo by SIMR)

From the fatigue investigations of pressed aluminium sheet the following main conclusions can be drawn:

- The fatigue tests of smooth specimens indicate that no account of prestraining as obtained during forming is needed in the fatigue life analysis as long as the forming strains is lower than 0.15. The same seems to hold also for the peak ageing state of the 6000 series materials.
- In both the strain controlled testing of smooth specimens and the fatigue testing of pressed sheet specmines it was found that the fatigue strength rank in accordance with the tensile strength of the materials.
- Finite element simulations incorporating both sheet forming and fatigue loading seem to be appropriate to establish the required stress concentration factors. The results of both the forming conditions and the stress concentration during fatigue agree with experimental results.
- The fatigue life estimation procedure for pressed sheet components based on the local strain approach turned out to work excellently; lives were generally predicted within-a factor of two both under constant and variable amplitude loading.
- Proper design of the transition from the pressing to the plane sheet has potenrial for improving the fatigue behaviour.

Casting properties

Castability (Volvo& Renault)

Each alloy have their own advantages depending on the required level of specifications. For economical constraint secondary alloy is optimum, for maximum ductility primary alloy is to be used while for easy recycling wrought aIloy is to be considered. VPDC is the most capable process for thin walled nodes while SSM produces more homogeneous characteristics in thicker sections.

Initial properties of AMCby Squeeze Casting (Alures)

AMCS can be conveniently used in the automotive field where high strenght and stiffness, at room or high temperatures are required. LSC process parameters have been ruled. ISC is the most convenient technology to produce high stressed near net parts

Near net shape parts properties (AMAG)

The castability of the AA6060 AISiMg-type wrought alloy by the indirect squeeze casting technique could be demonstrated. The advantages of the squeeze casting technique over pressure die casting are: the castings can be solution treated and aged yielding much higher strength levels, their ductility is much better*, they are pore-freee and therefore weldable; squeeze cast AISiMg-alloys can be further cold formed in the as cast condition and can be anodised. The mechanical properties of the forged components could not be reached, but they exceed those 0$ the pressure die =ast versions. On the other hand squeeze casting is much cheaper than forging.

ProfiIe properties

Initial & dynamic properties (Hydro Aluminium)

Characteristic mechanical properties for the alloys HA6060.85 and AMAG6082.2 relevant for design and manufacturing of automotive parts and systens have been generated. The presented data based on tensile testing and the fatigue data for combined torsion and bending are reievant for the selection of alloy and temper for lifetime considerations according to the agreed objectives for the Hydro Aluminium tasks.

The Vote model for calculating flow stress versus the strain has been verified.
The modeI allows for calculation of energy absorption under dynamic compression, for various profile geometry for strain rates between 0.003 & 1000 S-1 and strains 0.03 to 0.25.

Extrusion forming properties (AMAG)

The formability of profiles of AA6060 is little higher than that of AA6082. Because of the lower strength of AA6060 the brick spring effects are smaller. The mechanical properties of profiles of AA6082 depend significantly on the geometry of the profde and on the applicable cooling rate at the press. To maintain the formability and the potential of fu}l age hardening AA6082 has to be stabilised immediately after extrusion. The forming process is most advantageous executed at T1 or T1s condition and high strength components can be aged after forming. 3 point bend tests of units of a profile around the axis of bending of the real component provide the necessary formability data to adjust the forming forces.

Constant Amplitude fatigue (Volvo)

- Straining prior to the T5 heat treatment gave a slight improvement in strain- cycle fatigue properties for the 6060 alloy compared to straining after heat treatment which had the opposite effect
- The 6060 profile exhibited similar strain cycle fatigue lives and tensile strength properties for 3,5 and 2 mm wall thickness and in transverseflongitudinal directions.
- The 6082! alloy exhibit better shain cycle Fatigue properties compared to the 6060 alloy, particularly at small strain amplitudes.
- Good fatigue life predictions were obtained for the hollow square profiles 3/3.5, 6060-T5B. Maximum difference between the experimental and estimated lives were a factor of about two.

Random load fatigue (Renault)

A PC based software was developed to perform a fatigue life estimation of fatigue tests under random loading. It consisted of a rainflow counting analysis of the signal followed by a fatigue analysis. An elastic as well as an elasto-plastic analysis were used. A better correlation of the fatigue resuIts were obtained with the elasto-plastic analysis. This software is now available for design engineers. All the data needed for fatigue analysis has been determined in task 4.3 for 2 aHoys of the 6XXX serie.

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