Lightweight design of a suspension arm by friction stir welding

Jagger, Ian Michael

Durham University
School of Engineering

LIGHTWEIGHT DESIGN OF A SUSPENSION ARM BY FRICTION STIR WELDING

M.Sc. by Thesis

Ian Michael Jagger

Supervisor:
Dr. H Long
School of Engineering

2006

Summary

The research seeks initially to investigate why a greater shift to lightweight technologies for suspension design has not occurred already over the mass market vehicle sector. It outlines the 'knock-on' benefits of lightweight design and identifies roadblocks which hinder progress. Recent annual metrics of vehicle performance related to mass are investigated. Focusing on individual areas of the suspension, benchmarking identifies the best practice amongst current designs. Manufacturing and process engineering strategies are proposed to support the development of lightweight products with considerably improved environmental acceptability.

MIG (Metal Inert Gas) welding, universally accepted as the default joining technology in this field, was found to be restrictive to progress due primarily to detrimental effects on metallurgical, dimensional and process variation on both steel and aluminium products. The latest construction materials were reviewed for suspension application, but the focus remained on proposing lightweighting solutions for material generically available in economic volumes today, but with new joining technologies to overcome current restrictions in using less of these materials for each component.

Following a full review of the joining technologies available for automotive suspension construction, friction stir welding (FSW) was proposed as an alternative joining technology, with FSW replacing MIG in conjunction with extruded aluminium materials. This removed the barriers incumbent in the use of MIG, which demands a more conservative, heavier design to ensure adequate service lifetime.

Design concepts were engineered to take maximum advantage of the strategy of aluminium, extrusions, assembled with friction stir welding. Several viable designs were conceived, from which two were developed and compared. The optimum design was then carried forward into a manufacturing feasibility stage. The extrusions were developed for ease of manufacture, and friction stir welding trials progressed on coupons (plain plates) to ensure that the process was viable. Aluminium in the soft and hardened conditions in different thicknesses and joint configurations were successfully friction stir welded during the trial.

Future work would develop the extruded aluminium arm further, into the prototype phase, with sample extrusions being manufactured, FSW welded and assembled. Prototypes would then be rig tested to ensure mechanical and durability performance prior to vehicle trials. There are also possibilities in developing high strength thin wall multi-phase steel solutions, utilising Friction Stir Spot Welding (FSSW). This welding technology enhances the selection of high strength steels, as minimal strength is sacrificed during the joining operation.

Acknowledgements

The author wishes to thank One North East and the North East Productivity Alliance (NEPA) for funding support through the Engineering Fellows initiative: ThyssenKrupp, as my employer; Smart and ONERA for the loan of Friction stir welding facilities; and The Welding Institute (TWI), for advice and assistance with initial steel welding samples.

Contents

List of Figures

List of Tables

1 Introduction: Benefits of Lightweight Vehicles

The purchasers of motor vehicles are generally in favour of lightweight vehicles as a concept. However, in reality, for reasons of pleasure, lifestyle, practicality and perceived self-preservation, vehicles are selected which are laden with extraneous features such as Air bags, Multi speaker stereos etc. Marketing and legislation will ensure that this will remain the case for the foreseeable future, and therefore the only way to progress to reduced-weight vehicles is to lightweight the aspects of the vehicle which are mandatory, rather than deleting the accessory list. The principle 'mandatory' vehicle segments may be defined as Body, Engine and Chassis. It should be considered that with the scale of vehicle manufacture, typically 2000 examples of one model will be manufactured per day, with a model life of several years, and therefore seemingly modest weight reductions will have a significant cumulative benefit.

Body engineering has developed considerably in recent years, particularly with regard to higher strength steel applications. High strength steels are also permitting mass market vehicles to reduce their body mass whilst also improving crash performance. Aluminium solutions have also been developed, with different successful approaches from Jaguar and Audi in particular.

In engine development, designers have steadily been replacing cast iron by aluminium for engine blocks and heads. Where iron is retained, new forms such as CGI (Compacted Graphite Iron) (1), with twice the strength of Grey Cast Iron, are permitting lighter construction for engine structural applications. This is especially relevant to diesel engines, whose higher compression ratios have driven engine strength requirements which have historically only been resolvable by heavy construction techniques. Engine ancillaries such as inlet manifolds are increasingly moving further down the lightweight route, e.g. from aluminium to plastics.

In comparison to the body and engine sectors, chassis construction has seen evolutionary, rather than revolutionary advances. Whilst premium vehicles have often utilised aluminium components, usually of forged construction, mass market suspension systems have been predominantly steel of relatively modest grades, usually MIG or spot-welded. New manufacturing technologies such as hydroforming have been introduced, but increasing crash and fatigue requirements have prevented significant reductions in suspension mass, and material selection has been relatively conservative in comparison with other segments. The chassis area, rather than the two other primary 'mandatory' vehicle sectors, would appear to have most to gain from a lightweight strategy, but the constraints unique to the sector must also be considered. The complete suspension and steering system is safety critical to a greater or lesser extent. This is compounded by being more open to driver abuse than, for example, engines, which are now protected by rev. limiter systems. This combination of safety critical systems, also subject to overload conditions by the driver, is a potent argument for design conservatism, and it must be understood that progress must be made against a background of design integrity. In the following sections, the reasons for this conservatism will be explored and challenged, and proposals for change will be developed.

1.1 A Review of Vehicle Mass and Performance

To review the current industry position on lightweighting, it is necessary to look at the changing balance between weight, vehicle performance, engine size and fuel consumption. The suspension system accounts for approximately 12% of vehicle mass. In the absence of full year-on-year on the road vehicle data, indicative data was sourced from new vehicles tested (2) during each calendar year (2000/2005). From this information base it has been possible to re-organise the data to facilitate interpretation of the current status. Despite government pressures on emissions and the increasing cost of fuel, the opposing forces of crash safety and increased demands for luxury features have prevailed. Car weight has risen from an average of 1325 kg in 2000 to 1542 kg in 2005, as seen in Figure 1.

To attempt to offset this weight gain, manufactures have increased engine power; but at a slower rate. As seen in Figure 2, an average output of 199 bhp in 2000 has risen to 220 bhp in 2005. The power to weight ratio has therefore decreased, leading to an indication that performance will have been adversely affected. This is found only to be partially true: if acceleration is taken as the measure of performance, then it has indeed suffered, with the 0 to 60mph time extended from 7.6 seconds in 2000 to 8.4 seconds in 2005 as may be seen in Figure 1. However, if top speed is taken as the performance measure, then performance as shown in Figure 2 has increased from an average of 129 mph in 2000 to 134 mph in 2005 (2), despite weight having increased more considerably then power. This can be attributed to advances in vehicle aerodynamic efficiency, which confers a substantial advantage at high speed, but gives little benefit to acceleration performance, where mass is predominantly the controlling factor.

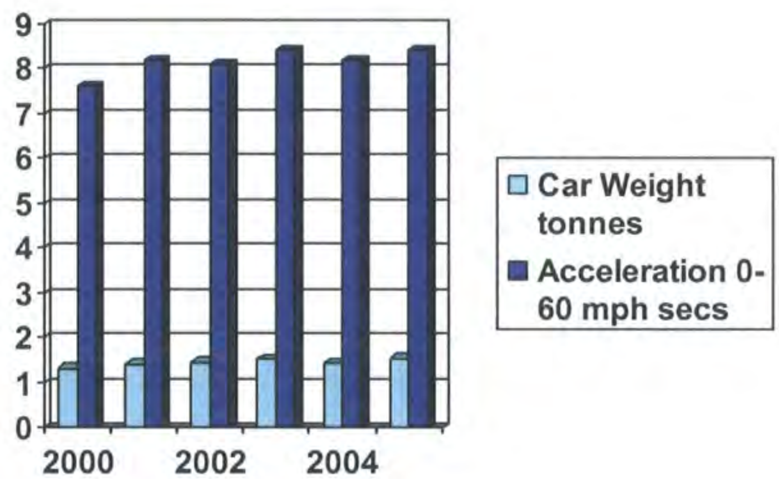


Figure 1 - Car Weight and Acceleration 2000/2005

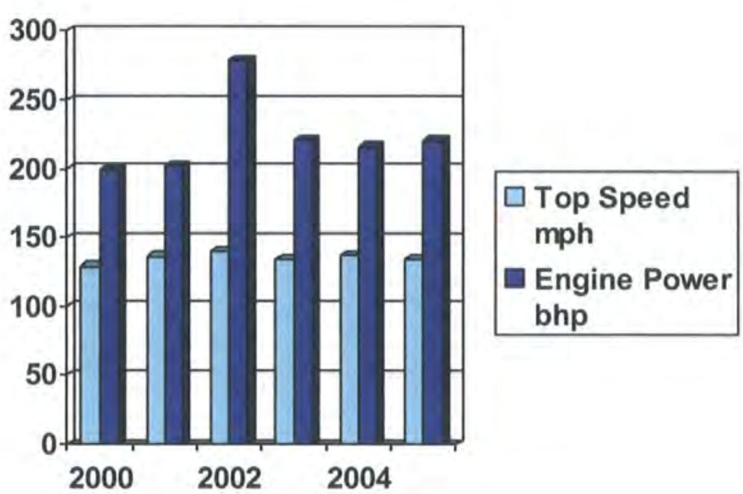


Figure 2 - Car Performance Parameters 2000/2005

Despite the increase in power output, engine size has levelled out, remaining at an average of 2.7 litres for the past 3 years, as shown in Figure 3. The small rise in power has therefore been due to increases in engine efficiency. It may be argued that the real improvements in engine efficiency are actually larger than those stated, as there has been a large scale transfer from petrol to diesel-fuelled vehicles during this timescale. These engines achieve their on-road performance through increased torque, power outputs being generally modest in comparison to petrol engines.

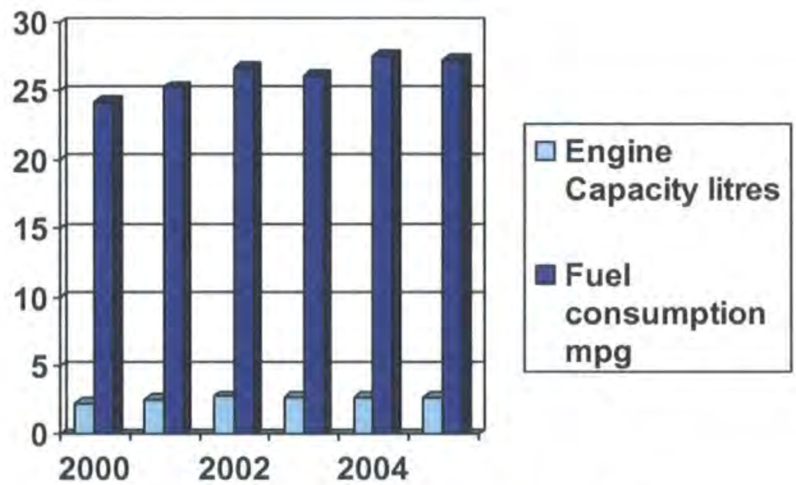


Figure 3 - Engine Capacity and Fuel Consumption 2000/2005

As also may be seen in Figure 3, despite the higher vehicle weight, increases in aerodynamic performance have assisted in permitting vehicles to achieve a reduction in fuel consumption from 24.2 mpg in 2000 to 27.3 mpg in 2005. It may be surmised that increased aerodynamic efficiency is capable of successfully masking increases in weight, but only under open road conditions. For stop/start motoring, it has been observed (2) that acceleration suffers most with added mass: fuel consumption and therefore emissions increase. Unfortunately, in this regard the heavy vehicle is at its worst around town, where increased emissions are most significant from an environmental health point of view. Lightweighting then, rather than increased aerodynamic efficiency, should be the aim if it is required that emissions are reduced in urban areas.

In addition to the dynamic advantages of suspension lightweighting, benefits also accrue from the passive mass reduction. As the mass of the vehicle is reduced, the engine specification may be reduced without detrimental effects on performance. With less power to transmit the suspension mass may be further reduced. The Virtual Mass Reduction Circle, as seen in Figure 4, has been developed to illustrate this beneficial cycle of events, and may be applied holistically and repeatedly to the vehicle, with a significantly advantageous effect on mass reduction.

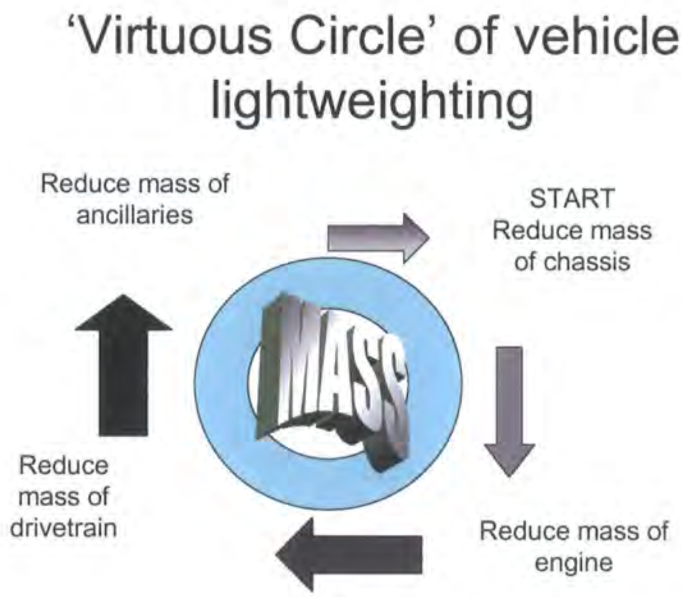


Figure 4 - Endless Lightweighting Opportunities from Virtuous Circle

Lightweighting of passive vehicle segments has a beneficial effect based simply on the basis of reduced mass. Increasing fuel prices are reducing the point at which a lightweight component may be justified in terms of whole vehicle life costs, against an initially less expensive but heavier alternative.

There are also additional benefits for dynamic components, as they have additional knock-on effects in improving fuel consumption, ride and handling which is not available from the other vehicle sectors. Each time the suspension articulates, the suspension arm rises and falls. The only power source available to drive this movement is the engine. Therefore lighter dynamic suspension components will reduce fuel consumption. The benefits for ride come from the ratio of sprung to un-sprung mass. A light suspension relative to the remainder of the vehicle will have a flatter ride profile, as the mass disturbed by road undulations will have less impact, due to less momentum, on the trajectory of the bodyshell. The handling of the vehicle also improves with lighter suspension, as the reduced suspension momentum permits the corrective forces emanating from the springs and shock absorbers to regain dynamic body control more quickly.

ULSAS (Ultralight Steel Auto Suspension) (3) is a comparatively recent study into lightweight automotive suspension design carried out by a consortium of steelmakers. The aim if the project was to demonstrate that steel can offer lightweight, cost effective structural automotive suspension solutions without resorting to newer alternatives such as aluminium, whose market share is increasing.

The study contained benchmarking reports which identified areas of potential improvement over existing designs. Innovations were then proposed to utilise new materials such as high strength steels and processes such as hydroforming and laser welding to offer new designs. The targets were generally to either replace current steel designs with lighter steel alternatives at the same cost, or to replace aluminium designs at the same weight and cost.

As part of the ULSAS Project (3), rear suspension design studies were carried out over a 2 year design period. The study concluded that it was possible to obtain lightweighting and cost reduction simultaneously when working in steel. One example was an independent rear suspension system shown in Figure 5, with a claimed 3% weight reduction and a 30% cost reduction when compared with an aluminium alternative. A rear torsion beam axle was also designed, offering a claimed 32% weight reduction without cost penalty.

Figure 5 - ULSAS Multi-Link Design

1.2 Organisational Lightweighting Strategies

In addition to the central technical focus of the lightweighting principle, it must be realised that lightweighting is also frustrated by some current business practices. The aim of this section is to consider how the automotive industry may structurally change in order to support lightweighting strategies. There is an established belief that cost, weight and quality are mutually exclusive: that it costs more to make a lighter part, and that quality resources must be increased to secure a better ppm (parts per million of good parts). For conservative strategies this may be true, but there are bold alternatives and strategies which are capable to provide simultaneous benefits in weight, cost and quality.

1.2.1 Geographical Integration The established system of vehicle assembly is by the tiered system. This is a pyramid arrangement comprising: the vehicle assembler at the top, several tier one system suppliers underneath, hundreds of tier two suppliers at the next layer down, with potentially thousands of tier 3/4/5 at the base supplying generally minor components such as fasteners. Each tier may be considered to control the one below; the whole working under the specification of the customer, or deferring to industry standards as determined by the customer.

This process has been maintained in established car-producing nations for many years, and must accommodate geographically large distances between suppliers and customers, with isolated pockets of specific design and manufacturing skills located considerable distances away from their customers and suppliers.

This remains the status quo, in part because suppliers feel comfortable with this arrangement. Each plant is a centre of expertise which is retained, managed, and protected on-site. Only components are shipped, not knowledge; this may result in easily defined boundaries and responsibilities, but the insularity is restricting and is preventing progress in many areas.

This problem is increasing as the industry evolves. In the UK, selection of lower cost suppliers in Eastern Europe can increase the supply line from tens or hundreds of kilometres to thousands. The developing automotive markets of Asia have learned from the inherent inefficiencies of this arrangement and, having the advantage of a relatively clean sheet of paper, appear to be aiming to concentrate all supplier tiers for a particular product type in a specific location.

China especially is developing specific cities or regions to be focussed on one market sector. This is a particularly strong strategy when selected manufacturing locations are underpinned by local natural resources, e.g. Iron ore, hydro electric supplies etc. The natural efficiencies of this arrangement will, over time, add to the competitiveness of the Chinese automotive industry when compared to the West.

If suppliers had closer geographic integration with their customers, then boundaries would be dissolved and lightweight strategies through, for example, component integration, would be rendered much easier. The geographical and tiered system limitations have led to a strict demarcation being drawn around the supplier's product, both dimensionally, financially and legally. To ensure adequate assembly and function, the supplier must conform to a tightly toleranced product, particularly at component interfaces where their product must fit to adjacent parts manufactured by other suppliers.

Due to the need for the sub-assembly to survive the journey to the customer, it must be complete in that it has to be in a form which is suitable to be protected from moisture, vibration, impact etc during transit. This is restrictive in that the most efficient level of assembly from a production engineering viewpoint may not be feasible due to a lack of robustness for shipping. An example is the ball joint protective shroud shown in Figure 9 which is fitted only to protect the joint during transit. There is a need then to build the essential elements of the product into some type of enclosure which demarks the extent of the product dimensionally and provides transit protection for shipment. This increases transient protection costs, as the packaging protection requirements for shipment may be higher than, or different to, the protection requirements when installed in the vehicle. With this eventuality the excessive packaging protection may be discarded upon fitment at the next tier, causing both needless packaging cost and environmentally insensitive packaging disposal requirements and costs.

Legally, the supplier's product (Tier 1 or 2 particularly) is often of sufficient size and complexity that its performance in service may be assessed independently to that of the tier above. These assessment tests; to determine robustness of the component or system in service, often overlap, and considerable savings could be made by eliminating the test costs of the subsidiary parts if the lower-tier product were incorporated in the higher-tier product prior to testing. Therefore removing geographic and demarcation boundaries would permit lightweighting through the reduced requirements to join sub-components, and the deletion of superfluous strength, corrosion protection and packaging requirements for sub-component shipping. In addition to lightweighting, other benefits such as reduced testing requirements and greater component confidence would accrue.

1.2.2 The Current Cost/Weight Reduction Process Cost reduction, as driven by the vehicle assembler, is an increasing challenge, imposed at the design stage, but also now revisited, often annually, within the product lifecycle. This is progressed by VA/VE (Value Analysis/Value Engineering) reviews (4), usually pre-production and held between the end customer and Tier1 suppliers. The focus of these costdown activities is to reduce principally the cost, and, secondarily, the weight of the existing product design.

These activities have been running for many years now, and with each component type having been reviewed several time with different teams, within the confines of the system described above, little further evolutionary progress may be forthcoming at component level. To develop further, a wider, more holistic approach may be required, and several possible strategies are discussed below.

(1) Initiating a strategic cost and weight reduction strategy. This may be considered as removing all the mass which is not required for the functionality of the product in its vehicle application. If the end product is examined for functionality in its installed location it will often be found to be carrying excessive weight and cost due to the manufacturing routes as described above. Non-essential mass, expensive tolerance requirements for inter-component assembly, high shipping costs for incomplete delicate components and multi-tier test costs being three of the excessive cost and weight drivers.

(2) The changing balance between initial cost and repair cost. It has previously been the norm to ensure that components known to be susceptible to early wear or potential in-service damage concerns have provisions built in to enable their exchange without replacing surrounding components (e.g. shock absorbers); this made economic sense at the time. However, increasingly onerous vehicle test and sign-off requirements have now ensured that all components which are not designed to be replaced as part of the routine service schedule (e.g. oil filters) are designed for the life of the vehicle. Therefore, except for crash events, the chance of a replacement being required is low and the overall significance of permitting replacement may be reduced. This removes the need to provision fastener features which permit replacement, such as bolts, clamps etc, and the designer may concentrate on reducing the initial cost and weight by deleting these 'service friendly' features as being a more efficient route to minimising whole life cycle costs. Lightweighting is then achieved by deleting features which are of no value to the mainstream customer.

(3) A 'one site' approach. Fundamentally, the integrated approach will place greater focus on the higher level supplier, usually the Tier 1 supplier. It will shift assembly processes from lower tiers to the Tier 1 plant. This has already happened for geographic and supply reasons between the end customer and Tier 1 suppliers, with Tier1 supplier-run satellite plants appearing line-side at vehicle manufacturers, but there are additional benefits in extending this below Tier1 and adding a lightweighting and quality to the cost reduction approach. The approach is only fully valid for high volume applications as found in the automotive sector, where the relocated manufacturing equipment would have a high utilisation factor in its new application. This is best illustrated by a number of proposed examples from the automotive suspension arena.

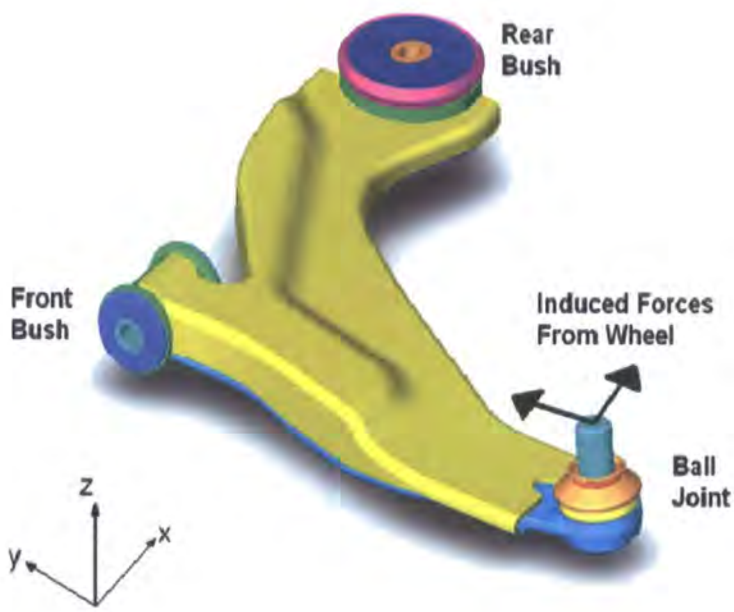


Figure 6 - A Suspension Arm with Fitments

Example 1: Suspension Ball Joints Figure 6 shows a Steel suspension arm with Ball Joint. Ball joints are required as a feature of suspension arms to locate the road wheel and permit articulation of the arm under suspension loading. They are currently supplied from a Tier 2 specialist ball joint manufacturing plant, and pressed into the arm at the Tier 1 supplier. The ball pin is housed and constrained within a turned outer with a wear-resistant cup which is accurately machined on its outside diameter. The ball joint assembly is then pressed into a carefully machined outer bore in the arm. These fits are inevitably safety critical.

A significant proportion of component cost and weight is in engineering and supplying the accurately machined ball joint outer and controlling the assembly fit. This part could be engineered out entirely with the pin and cup located and assembled directly into the arm. The advantages would include weight and cost savings, improved dimensional stability and design cost, and increased quality from the elimination of need to control a safety critical interference assembly process.

Significant changes would have to occur to bring these major cost and weight savings to fruition: The ball joint supplier would supply fewer components, but would be required to contribute expertise to the customer to integrate his supply into the arm with no loss of function. Secondary assembly processes such as applying lubricant to the arm would also be transferred. Also, the legal responsibility in the event of failure between the two parties may be less well defined with an integrated approach. The ball joint supplier may be obliged to accept responsibility for the assembly of the integrated product, if not the design.

Example 2, Steering Rack Body The steering rack usually mounts on top of the front subframe and transmits the steering input through a servo hydraulic or electro hydraulic force magnifier into the track rods. The working elements are the toothed rack, pinion and shaft mechanism, a tubular enclosure (steering rack body) which contains the rack and oil bath lubricant, and the force magnifier. The force magnifier has usually been hydraulic, but is increasingly electro-hydraulic, or fully electric, which is more energy efficient as it removes the requirement for a continually driven hydraulic pump. Visually the assembly appears as a complex cast aluminium tube which encompasses the rack. It is usually bolted to the top of the subframe prior to assembly of the subframe module to the vehicle. The steering rack body provides significant functionality: it provides attachment points for the rack to the subframe, permitting the rack loads to be reacted. It also supports the rack bearings and seals the rack in a clean environment (hydraulic design) to protect the innards from mechanical damage and contamination.

With an integrated design, all the functions of the steering rack body casting may be provided by the subframe, no rack fixings would be required, and bearings and seals would be provided within the subframe crossmember. This methodology may simplify further with the advent of EPAS (Electric Power Assisted Steering). The following advantages would accrue for an integrated design: Total elimination of an expensive cast alloy steering rack body and fixings which would provide major cost & weight benefits. Additionally, the dynamic response of the vehicle would benefit from the improved consistency of steering geometry (1 set of variation-inducing fixing attachments are eliminated). Steering feedback would also improve, as the rack then runs through the centre of a stiff frame, there is reduced flexing of its mountings.

Again, a closer co-operation would be required between supplier and customer. Consideration would have to be given to incorporating functional features of the steering rack body into the frame. The housing within the subframe, for example, may have to be sealed more effectively against contamination for a hydraulic system than for an EPAS system. The engineering of the system would be shared between the subframe and rack manufacturers. The internal rack components would be supplied from the rack supplier's plant, pre-assembled as far as is feasible, ready for final assembly into the frame at the Tier1 plant. It is envisaged that the rack supplier would be contracted to support productionisation and manufacture.

Example 3: Rubber Bush Outers Figure 6 shows a suspension arm with a solid rubber front bush and rear hydrobush. Conventional rubber bushes comprise two concentric tubes with the interspace injected with rubber, the whole component then inserted to a third tube affixed to the product as seen in Figure 6. Following the logic of the first two examples, it may be assumed that it would be proposed here that rubber bush technology could be streamlined by injecting the rubber directly into the component. It would be convenient if all rubber bushes with steel or plastic outers may be replaced by rubber directly moulded into the bore, eliminating the outer. This cost and weight saving is unfortunately frustrated by the need for the rubber to be set into compression in order for it to be durable, especially in high load suspension applications. This requires the outer to be reduced in diameter (sized) after moulding which is difficult to perform in most applications where the outer tube is already installed as part of a fabricated assembly.

This restriction does not apply to hydrobushes (rubber bushes which are fluid filled), which are built into a can at the moulders prior to shipping to the Tier 1 supplier. The rubber is pre-compressed in a different manner with this type of bush, permitting a novel approach to be considered. If a component integration approach is taken, then the hydrobush inner could be built into a can formed as part of the clevis (the bracket mounting the arm to the subframe), therefore fully eliminating the can. The advantages of this proposal would be that the full cost and weight of the hydrobush can would be eliminated.

A new customer relationship would be formed to facilitate this advance. In this specific case the rubber moulded parts would be supplied moulded from the bush company. However, the fluid fill would take place at the Tier 1 supplier, along with the closure sealing. This, and final bush assembly qualification, would be progressed by Tier 2 bush supplier personnel within the Tier 1 supplier facility.

1.2.3 Package Pressures

Every new generation of vehicles increases the pressure to improve packaging efficiency. This is a volumetric measure concerned with increasing the percentage of internal space available in the vehicle for passenger's use, at the expense of the space allocated to vehicle systems. This is achieved by commensurately reducing the space which is available for the functional components such as suspension. This in turn tends to condense more mechanical functionality into less space, resulting in a need for more complex shapes which in turn requires increasingly difficult to draw pressings. This limits material selection to the high elongation end of the spectra. High elongation invariably means low strength; constraining components to be heavier sections. Additional package constraints may therefore be seen to result in added mass. Therefore the opposite must be true, and if package constraints may be relaxed, then a designer may be able to open out the sections to permit a thinner gauge, lighter design. This may be realised by increased liaison between body and suspension engineers at the design concept stage.

This section has illustrated that there are lightweighting opportunities to be gained from organisational improvements. If supplier's facilities were available on the suspension arm manufacturing site then, for example, rubber bushes could be moulded in-situ and ball joints pins could be assembled directly into the arm. This would allow the deletion of bush outer metals and ball joint housings; substantially further reducing weight and cost. However, these potential gains are additional to the main content of this thesis; the redesign of a suspension arm in lightweight materials with novel welding processes.

2 Vehicle Suspension Assemblies

The scope of the vehicle architecture which is selected for investigation is focussed on lightweight automotive suspension structures such as the pair of steel rear suspension arm illustrated in Figure 7. The definition excludes the body in white, which is generally of thinner grade materials, and predominantly a STATIC structure. The components which are generically covered by the suspension structure definition are predominantly DYNAMIC, moving in response to road wheel articulation and body responses, and include suspension arms, axles and sub frames. The dynamic nature of the components usually determines that fatigue is a significant design constraint; other predominant design constraints being strength, stiffness, corrosion and crashworthiness, which are mutually opposed to the desirability of producing a lightweight component.

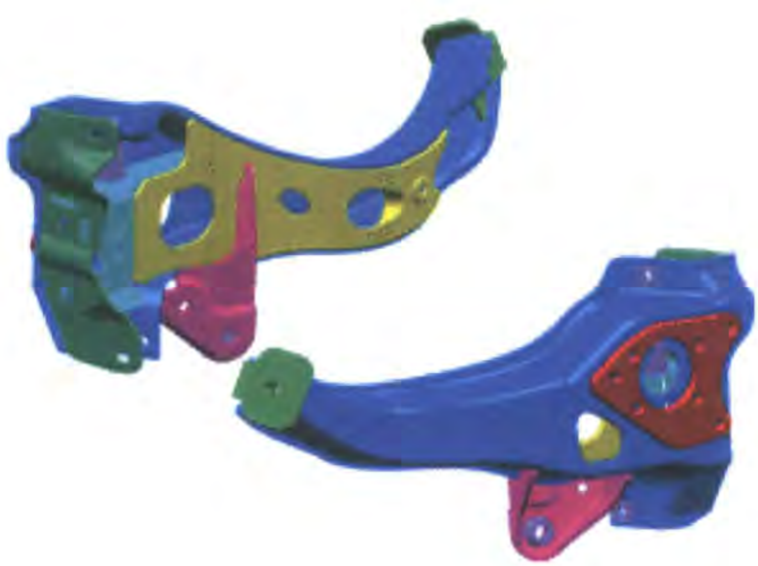


Figure 7 - Example of a Pair of Pressed and Fabricated Steel Rear Suspension Arms.

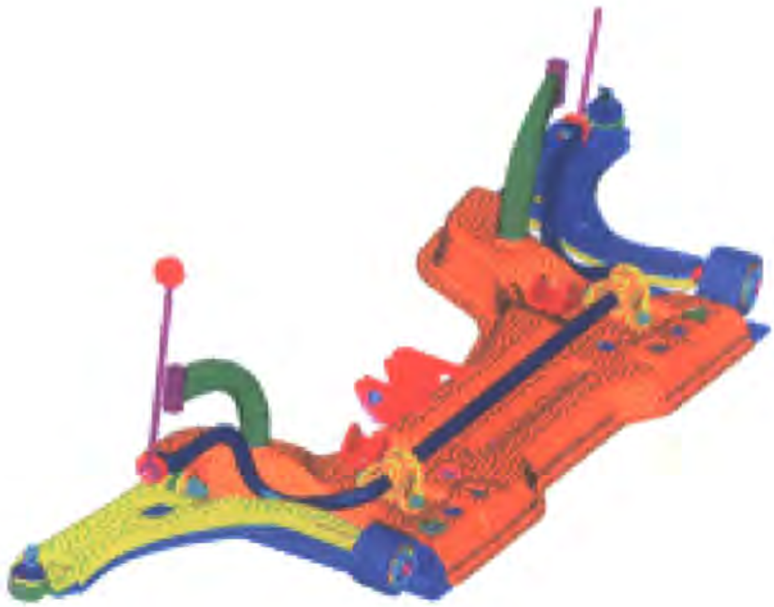


Figure 8 - A Steel Pressed and Fabricated Front Suspension Module

For ease of manufacturing in a vehicle assembly plant, the assembly process is usually sub-divided into modules. These vary according to the vehicle, but typically the body would be the primary assembly, and that sub-assemblies, or modules, would be brought to it by a conveyor system. The modules which are of concern to this work are the front and rear suspension modules, of which Figure 8 gives an example. This consists of a subframe (brown), suspension arms (yellow and blue) and anti-roll bar assembly (dark blue) with drop links (pink).

2.1 Suspension Architecture

Suspension architecture varies considerably between vehicles. It is defined individually for a vehicle or a range of vehicles sharing a common sub-structure (a vehicle platform). The architecture will depend on major factors such as whether the vehicle is for on-road or off-road use, driven by the front wheels, rear wheels, or all wheels (4WD); whether the driveshafts are considered part of the drive train rather than the suspension, and if a wheel is driven or not is significant for the suspension architecture. Many other factors affect the architecture: the vertical wheel travel required, maximum wheel and tyre size specified, plus access for snow chains which are now a mandatory requirement in many markets. The architecture also has to support the maximum vehicle mass, laden and unladen, over a wide range of front to rear weight distribution. Cost is also a major factor; an independent suspension system will usually provide superior characteristics, but at additional cost and often increased space requirements. Minor factors may include the balance between vehicle handling and ride. Many minor factors involving ride and handling are initially estimated by software packages and subsequently optimised by ridework exercises, once prototype vehicles are available.

Whilst chassis architecture varies enormously between brands and models, there are several generic component types which may be identified as potential targets for lightweighting, which it is important to have considered.

Subframes The subframe, as shown in Figure 8, is usually the base on which the suspension system is constructed. The subframe acts as the mounting point for suspension arms, steering racks, anti roll bars etc, and controls much of the suspension geometry. They may also take engine static or dynamic loads, and exhaust loads, with associated thermal issues.

The subframe is usually mounted to the vehicle body vertically, from underneath, at four or more mounting points, often through four tuned bushes which seek to isolate road, and possibly engine vibrations from the occupants. The subframe also plays an increasing part in crash management, but this does not have to result in the frame becoming stronger and heavier. The subframe may usually be optimised for crash if it collapses in such a manner that it absorbs the maximum energy over the stipulated intrusion distance whilst preserving the integrity of the passenger space. This is compatible with lightweight design, the important factors being closer integration of subframe and body designs and careful setting of intrusion targets to manage the controlled collapse of structural sections, perhaps utilising collapse initiation features at critical points.

The subframe illustrated in Figure 8 is of fabricated pressed steel construction which is typical of designs for smaller vehicles (B to C class). For larger vehicles (C to D class), an alternative tubular design is often used. This may have six rather than four bodymounts (bushed mountings to bodyshell). This type of frame is larger and projects closer to the front of the vehicle, where its additional mass is compensated by taking a greater share of the crash management responsibilities from the body structure.

Suspension Arms Suspension arms are also referred to as control arms or wishbones. Historically, control arms are usually associated with McPherson strut type suspension systems and wishbones with twin arm systems, i.e. 'double wishbone' designs. For the purpose of this study, the suspension arm will be considered as the main, lower suspension arm as seen in Figure 8. Upper suspension arms may also be specified, particularly on double wishbone independent suspension systems. The suspension arm is located close to the wheel hub, where it is attached through a ball joint which permits suspension articulation and steering, see Figure 9 for a cross-section of a ball joint design.

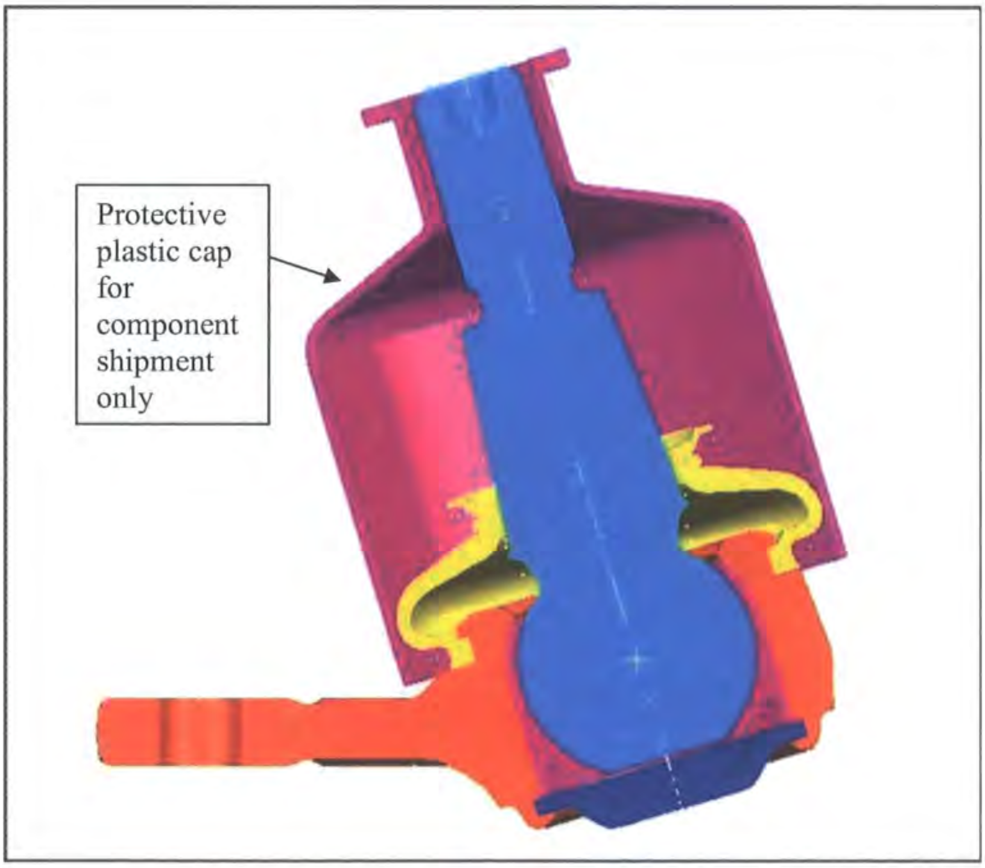


Figure 9 - Control Arm Ball-Joint Assembly

The arm is located inboard through two solid or hydraulic rubber bushes to the subframe. The arm and bushes are designed to permit the arm to articulate vertically in response to the wheel movement. The bushes are carefully tuned in all axes to have the optimum static, dynamic and vibrational responses, to provide optimum tuning performance in response to the required vehicle characteristics. In crash, the arm should deform before damage is caused to the subframe. Collapse initiation features may be introduced to the arm to promote this effect.

Front Bush & Rear bush designs for arms may both be either horizontal or vertical axis bushes, dependant upon the dynamic characteristics required. This is considered as axis locations influence which arm design is most suitable. For example an aluminium extrusion or a one-piece steel design is easier to form if both bushes are arranged on a vertical axis.

Most steel fabricated designs are two piece, which does not include optional additional internal stiffeners. Some designs are one piece, which are easier and cheaper to manufacture, but may have package space limitations as they require a larger footprint (as viewed in Z direction).

Anti Roll Bar Systems (ARB) The anti roll bar system comprises the bar itself, two rubber mounting bushes and associated bracketry to locate the arm to the subframe. as shown in Figure 8. To accommodate suspension movement and ensure that the ARB is loaded in a purely torsional mode, a pair of drop links, incorporating a small ball joint at each end, are utilised to connect the ends of the bar to the vehicle body. The purpose of the bar is to resist torsional inputs through the intrinsic stiffness of the bar in rotation. In this manner the ARB adds stiffness to the vehicle suspension in roll, i.e. when cornering, but does not add stiffness when a bump is encountered on a straight road, as both ends of the bar move together in the vertical plane. In this manner a comfort-orientated suspension is provided under steady state driving conditions, automatically stiffening to provide greater roll resistance on bends. Recent enhancements to these systems include hydraulic control of the bar to artificially tune the stiffness response. These give most benefit to off-road vehicles, but at a cost and weight penalty.

Steering Rack The steering rack comprises a rack and pinion assembly, or similar, and converts the rotational movement of the steering wheel and column into linear movement of the tie bars, and hence the roadwheels. The system is usually power assisted to reduce effort and allow higher steering ratios (rotation of steering wheel v angular steering displacement) to be utilised. Assistance is usually hydraulic, although electrically assisted systems are in the ascendancy. The steering rack usually sits on top of the subframe, and is considered part of the front suspension module, although it is often contributed by a different Tier 1 supplier.

2.2 Benchmarking of Suspension Control Arms

Suspension arms usually consist of two rubber bushes for location and isolation and a ball joint for attachment to the wheel knuckle. All are joined by an arm, usually a steel pressing, which locates the wheel and transmits loads to the chassis/body.

Selecting a major component for lightweighting requires an understanding of products in the current marketplace. A benchmarking study was therefore developed, taking arms from a range of brands and model classes. Table 1 illustrates the selected control arms on the current market between 2005 – 2006 and their weights. Generally, a heavier vehicle will require a heavier arm to support it, therefore arm weights tend to increase in line with vehicle mass, it is therefore broadly illustrative to calculate the ratio of arm mass to vehicle mass to give an indication of lightweighting efficiency.

Depending on these ratios the ranking of each arm is given in the table. Other data collected includes the thickness and yielding strength of primary arm material, ball joint type, front bush and rear bush design and the number of primary pressings. The bush design data is included because whether the bush is located horizontally or laterally can affect the manufacturing technology selected.

Table 1- Suspension Arm Benchmarking Data

Model	Model Details	
	Lightweight ranking: 12	Thickness: 2.3 mm
	Mass of arm: 3.49 kg	Yielding stress: 350 MPa
	Mass of vehicle: 895 kg	Ball joint type: Taper Pin
Audi A2 (2005)	Ratio of arm & vehicle mass: 0.39%	Front bush: Horizontal Rear bush: Horizontal No. of pressings: 2
	Lightweight ranking: 11	Thickness: 3.0 mm
	Mass of arm: 4.31 kg	Yielding stress: 420 MPa
	Mass of vehicle: 1137 kg	Ball joint type: Straight Pin
Ford Fiesta (2005)	Ratio of arm & vehicle mass: 0.38%	Front bush: Horizontal Rear bush: Horizontal No. of pressings: 2
	Lightweight ranking: 10	Thickness: 2.8 mm
	Mass of arm: 4.65 kg	Yielding stress: 500 MPa
	Mass of vehicle: 1250 kg	Ball joint type: Taper Pin
Ford Focus (2005)	Ratio of arm & vehicle mass: 0.37%	Front bush: Horizontal Rear bush: Horizontal No. of pressings: 2
	Lightweight ranking: 8	Thickness: 2.8 mm
	Mass of arm: 4.63 kg	Yielding stress: 450 MPa
	Mass of vehicle: 1375 kg	Ball joint type: Straight Pin
Ford Mondeo (2005)	Ratio of arm & vehicle mass: 0.34%	Front bush: Horizontal Rear bush: Vertical No. of pressings: 2
	Lightweight ranking: 13	Thickness: 3.0 mm
	Mass of arm: 6.17 kg	Yielding stress: 450 MPa
	Mass of vehicle: 1480 kg	Ball joint type: Taper Pin
Ford Mondeo (2006)	Ratio of arm & vehicle mass: 0.42%	Front bush: Vertical Rear bush: Horizontal No. of pressings: 2
	Lightweight ranking: 3	Thickness: 3.0 mm
	Mass of arm: 2.6 kg	Yielding stress: 380 MPa
	Mass of vehicle: 1015 kg	Ball joint type: Taper Pin
Honda Jazz (2005)	Ratio of arm & vehicle mass: 0.26%	Front bush: Horizontal Rear bush: Vertical No. of pressings: 1

Model	Model Details	
	Lightweight ranking: 7	Thickness: 3.0 mm
	Mass of arm: 3.83 kg	Yielding stress: 350 MPa
	Mass of vehicle: 1200kg	Ball joint type: Taper Pin
Nissan Almera (2005)	Ratio of arm & vehicle mass: 0.32%	Front bush: Horizontal Rear bush: Horizontal No. of pressings: 2
	Lightweight ranking 9	Thickness: 3.0 mm
	Mass of arm: 4.89 kg	Yielding stress: 350 MPa
	Mass of vehicle: 1325 kg	Ball joint type: Taper Pin
Nissan Primera (2005)	Ratio of arm & vehicle mass: 0.37%	Front bush: Horizontal Rear bush: Horizontal No. of pressings: 2
	Lightweight ranking: 4	Thickness: 4.0 mm
	Mass of arm: 3.65 kg	Yielding stress: 400 MPa
	Mass of vehicle: 1385 kg	Ball joint type: Taper Pin
Renault Laguna (2005)	Ratio of arm & vehicle mass: 0.26%	Front bush: Vertical Rear bush: Vertical No. of pressings: 1
	Lightweight ranking: 2	Thickness: 4.0 mm
	Mass of arm: 2.78 kg	Yielding stress: 420 MPa
	Mass of vehicle: 1175 kg	Ball joint type: Straight Pin
Renault Megane (2004)	Ratio of arm & vehicle mass: 0.24%	Front bush: Horizontal Rear bush: Vertical No. of pressings: 1
	Lightweight ranking: 5	Thickness: 3.2 mm
	Mass of arm: 2.6 kg	Yielding stress: 500 MPa
	Mass of vehicle: 840 kg	Ball joint type: Taper Pin
Toyota Yaris (2005)	Ratio of arm & vehicle mass: 0.31%	Front bush: Vertical Rear bush: Horizontal No. of pressings: 1

Model	Model Details	
 **Vauxhall Corsa (2005)**	Lightweight ranking: 6	Thickness: 3.5 mm
	Mass of arm: 3.39 kg	Yielding stress: 480 MPa
	Mass of vehicle: 1067 kg	Ball joint : Straight Pin
	Ratio of arm & vehicle mass: 0.32%	Front bush: Horizontal Rear bush: Vertical No. of pressings: 1
 **Vauxhall Vectra (2005)**	Lightweight ranking: 1	Thickness: Solid Section
	Mass of arm: 2.93 kg	Yielding stress: Al. Alloy
	Mass of vehicle: 1365 kg	Ball joint : Straight Pin
	Ratio of arm & vehicle mass: 0.21%	Front bush: Horizontal Rear bush: Horizontal No. of pieces: 1 cast Al.

Analysis of benchmark data. As may be seen in Table 2, the only aluminium design arm considered (Vauxhall Vectra) was easily the most mass efficient, with a Component weight to Vehicle weight ratio of 0.21% The manufacturing costs and sale prices to the OEM (Original Equipment Manufacturer) would be confidential information; however, the retail cost of this component was determined from a dealer and found to be almost twice that of a comparable steel arm. (The main dealer price in Jan 2006 for each arm, complete with ball joint and two bushes is £85 to £87 for the steel Mondeo arm, and £155 for the aluminium Vectra item.)

This indicates that an aluminium arm with a more efficient use of materials has the potential to maintain an optimum lightweight performance at reduced cost. If the aluminium arm is excluded on cost grounds, the most efficient steel designs are the one-piece pressings of the Renault Megane and Honda Jazz. This design manages to avoid welding issues, the downside being that they are generally of larger cross section for strength and stiffness reasons, which may cause package issues. One piece steel arms are mass efficient but require more package space. They also function best if both bushes are constrained to a vertical axis only, as this permits a vertical press fit suitable to engineer in a one-piece design.

Table 2 - Results of Arm Benchmarking

	Primary Advantage	Primary Disadvantage
1, Aluminium	Weight	Cost
2, One Piece Steel	Cost	Package Space
3, Two Piece Steel	Strength	Weight

The new Mondeo arm has increased in mass as a function of: increasing crash management responsibilities accorded to the suspension system, increased refinement standards, enhanced durability requirements and a general increase of the vehicle mass. All these factors are important to the OEM, and all act against the requirement to lightweight the component.

Considering that the component carries out a similar function in all the vehicles, there was a significant lack of consensus with regard to the optimum design of the subsidiary components. Five arms have straight pin ball joint designs, the remainder taper pin. Three front bushes and five rear bushes were vertical, the remainder horizontal.

From the benchmarking study, steel products were dominant, but the conclusion drawn was that an aluminium based solution would be optimum, if a design was available which used the more expensive material more cost effectively.

3 Limitations of Current Manufacturing Technologies, Joining Processes and Materials

3.1 Summary of Manufacturing Processes

This section covers manufacturing processes relevant to the manufacturing of suspension components. Many manufacturing processes for steel and aluminium suspensions are similar, despite Young's Modulus for Aluminium being around only one-third that of Steel. Therefore to replace steel with aluminium under the same design concept with stiffness as the design limitation will require significantly thicker sections. The strength of aluminium is determined by alloying and heat treatment, but is generally lower than steel. This would detrimentally offset weight savings and increase cost further. To be efficient in lightweighting, designs must be produced specifically for aluminium; modified steel designs generally cannot effectively be re-optimised for aluminium. Forged, Pressed Sheet, Cast, Squeeze Cast and Extrusion based alternatives remain as the principle manufacturing methodologies for aluminium.

Forging Forged designs are often specified in aluminium for upmarket vehicles, but are usually difficult to justify on cost grounds for mass market vehicles. Forged steel components are strong but heavy and are often used on off-road vehicles. However, forgings may occupy a niche market where packaging constraints demand that a functionality of strength with minimal cross sectional area is required. Work hardening and the residual compressive stresses imposed by the forging process are beneficial in cancelling out the imposed tensile stresses which are the most damaging for fatigue life.

Casting Cast designs, usually gravity die castings, require thick sections, offer limited strength, exhibit restricted homogeneity and tend to be utilised principally for compact suspension components such as knuckles. Porosity remains an issue, potentially reducing strength and fatigue life in a random manner. Expensive post production sectioning tests or radiography may be required to control these limitations.

Squeeze Cast Squeeze cast components exhibit properties between those of straight die cast and forged components. It is applicable to Aluminium or, for increased cost and lightness, Magnesium (5). For aluminium, this must be considered to be a technology with growth potential for lightweight suspension applications, as thinner-wall products may be produced. However many of the limitations of general castings still apply, particularly long cycle times, and the increased complexity of the squeeze cast process further adds to the high capital costs.

Pressed Sheet Pressing is a ubiquitous process for steel. Sheet based aluminium alternatives may be manufactured by similar sheet forming processes. Blanks would be manufactured on a blanking press and formed through several transfer dies to a final shape. The process is viable provided that known characteristics of aluminium pressing technology are considered, such as die pickup and tearing, which renders the process less robust than steel pressing. The thicker material sections required to replace steel add to the challenges, as it is more difficult to press a component of given elongation in a thicker section.

Forming and Hydroforming Whilst pressing remains as the fundamental forming process, hydroforming (6) has been selected as the manufacturing process for several suspension applications, particularly for tubular subframes with high crash functionality. Hydroforming from a base tube has been in use for many years now for steel components. Hydroforming is a low variability process which delivers a product with excellent dimensional stability. The changes of section permitted by the process have the ability to reduce the piece part count considerably by designing-in features. The resulting reduction in weld requirements adds to the cost saving. Some limitations are that the design must be signed-off early to permit the substantial dedicated die tooling to be manufactured, and that any subsequent changes have a severe effect on the timing and economics of the process. Capital costs for hydroform presses and specialist tooling are high. Hydroforming remains a useful niche option for lightweighting with steel.

Tubes may also be manufactured from sheet aluminium, as well as seamlessly by extrusion, as discussed below. These may be utilised either as manufactured or

Hydroformed. Hydroforming aluminium is a similar process to hydroforming steel, and confers similar benefits and limitations.

Aluminium, despite being a softer material, is perceived to be more difficult to hydroform. In the study by Hunter (7), this is due to limited elongation, typically 20% maximum, in comparison with 50% for Steel, this limits diametrical expansion. Two less obvious factors also restrict aluminium's suitability for hydroforming: Uniform Elongation Limitation and the strain hardening of material flow stress. These and other material constraints are more likely to cause local strains during the hydroforming process, leading to tearing and rupture of the tube. Furthermore, to benefit from the advantages of hydroforming extrusions, the challenge of sealing the complex tube end profile when pressurised must be overcome.

Extrusions Extrusion is a manufacturing process available for aluminium which is not viable for steel due to its restricted ductility. Extrusion may be used as a device to compensate for the intrinsic weaknesses of aluminium by increasing section dimensions and thicknesses only where required to meet strength and stiffness requirements (8). Extrusions would be delivered to the Tier 1 site in lengths of several metres, and would require only cutting to length prior to fabrication. Extrusions may also be hydroformed, but sealing of a non-circular or multiple orifice shape at each end of the hydroformed component is significantly more difficult. Also, the wall thickness of extruded sections can vary by up to 10%, causing inconsistent product to be manufactured. From the above, Aluminium Extrusions must be considered one major possibility for a lightweight suspension strategy, but it remains to be considered whether it is sufficiently compatible with MIG welding and, if not, to determine a better fabrication process.

3.2 Summary of Joining Processes

3.2.1 Fusion Welding Technologies Currently, two fabrication technologies dominate the majority of suspension applications; both require the material to become molten at the point of welding. MIG welding is the primary technology, Spot welding being the other.

MIG Welding MIG (Metal Inert Gas) welding comprises a copper coated metal wire which is delivered robotically to the weld location and consumed by the arc in the production of the joint. The weld must be protected from the atmosphere by a shielding gas to avoid oxidation. The weld may be continuous or intermittent to suit the design requirements. MIG welding may be adapted for Aluminium or alternatively TIG (Tungsten Inert Gas) welding may be utilised, which gives a beneficially softer arc, but is more difficult to productionise. MIG welding tends to be used on thicker material sections. MIG welding may be applied without need for any reaction force at the joint, permitting flangeless designs.

MIG welding has many limitations as a robust, repeatable fabrication method. Most of these are derived from the fact that it fully re-melts the parts to be joined. This effectively returns the steel to the as-cast condition, losing any work hardening benefits gained in the foregoing forming operations and introducing inconsistent and weaker microstructures in the weld. As the weld cools from its molten weld-induced state, the high temperature variations across the component generate a mixture of distortion and residual stresses. These are highly detrimental to the functionality and durability of the part respectively. The residual stresses constrained within the material may be as high as yield and must be considered in the design process. This renders even approximate estimates of fatigue life difficult for CAE technology, and it cannot be satisfactorily evaluated until prototypes are fabricated and physically tested.

The process robustness of MIG welding is intrinsically poor, due to the quantity of parameters implicit in the welding process. Many variables in each element of welding equipment or consumable must be controlled and held within acceptable parameters if a satisfactory component is to be produced; these include the welding set-up: robot, torch, shroud, and welding fixture, not overlooking the variations in dimensional accuracy of the components to be fabricated. The time at which an assembly is held at each welding stage also affects the proportion of thermal contraction which manifests itself as distortion, and how much remains as residual stress. The order of welds may be controlled through robot sequence programming, but the process time variations are practically difficult to eliminate, and may result in supposedly identical components exhibiting variations in service performance, including dimensional and durability variations.

MIG welding also adds mass by application of the weld metal. This may be seen as a disadvantage for lightweighting now that there are alternatives which add little or no mass to achieve a joint. Higher strength steels bring additional challenges to fusion welding with higher clamping loads and loss of properties (9).

The variable residual heat in components throughout a plant frustrates accurate metrology measurements. Only fully cooled parts should therefore be measured. The intrinsically volatility of the arc welding process exacerbates the difficulty of controlling the above, as wire and coating residues are consumed, spatter (globular emissions from weld pool) may be discharged from the weld, requiring regular maintenance input to clean this spatter from fixturing etc. within the required standards. Unless rigorous cleaning procedures are adopted, the fixtures will lose dimensional accuracy and the fabrication may drift outside acceptable tolerances. Non-fusion welding processes would avoid these issues as the processes have intrinsically greater control of variability.

'The Environment' and 'Occupational Health' are two areas of rapidly increasing relevance to manufacturing and particularly welding (10). MIG welding has several characteristics which need careful management: The arc cannot be viewed with the naked eye; dark glass protection is therefore required against arc-eye, and against the hot molten metal which may be emitted with high velocity from the weld pool. Protection is also required to handle the components, which are very hot post welding. Welding fume must be removed from the building, extraction systems are required to remove the fume from the plant, which must be purchased, installed, powered and cleaned. The effect of such emissions on the atmosphere is under increasing scrutiny, and the pressures on fusion welding in this regard can only increase. This is an important factor for process selection, as any process used must be viable in a scenario of mandatory conformance to burgeoning Environmental and Occupational Health legislation. Again, alternative non-fusion welding processes would minimise or eliminate all these issues. The detrimental effects of MIG welding are more prevalent for aluminium than steel, due to factors involving the oxide layer, the increased thermal conductivity and other metallurgical effects which are discussed in more detail in the Aluminium Section, 3.3.2.

Resistance (or Spot) Welding During spot welding, two or more thicknesses of material are heated by electrical resistance between two electrodes. The interface becomes molten and fuses. No consumables are required, although tips require regular replacement. Spot welding tends to be utilised on thinner materials, especially steel, and requires access to both sides of the joint, usually resulting in flanged designs which will not then permit optimum use to be made of the available package space.

Spot welding enjoys limited functionality for Aluminium in comparison to steel (11) due to inconsistent effects of the oxide layer which may produce unreliable results. The high thermal conductivity of Aluminium transfers the resistance-induced heat rapidly away from the weld in comparison to steel, increasing energy cost and distortion, therefore this technology is not considered acceptable for the requirements of this research.

TIG Welding TIG (Tungsten Inert Gas) is a derivative of MIG welding. The arc produced is not as harsh and is more suited to a lower melting point material such as Aluminium. It retains most of the metallurgical disadvantages of MIG and is slower, so is not considered further here.

Laser Welding Potential laser welding applications may be one of two types. CO2 lasers control the beam application by mirrors, and are ideally suitable for 2D application such as cutting blanks. This technology is being further developed as 'remote laser welding'. In this arrangement the mirror is manipulated to about 500mm from the weld and hence adds considerable access flexibility to the CO2 process. The shorter wavelength of Nd YAG lasers allow the beam to be constrained within a fibre-optic cable and mounted on a robot. These are then suitable for 3D operations, rendering them considerably more useful for cutting and welding on chassis applications than non-remote CO2 processes.

Lasers produce a consistent weld with minimal distortion providing that there is zero fit up gap, this is possible to achieve by flattening the panels together by roller on body-in-white (bare untrimmed bodyshell) applications. This is utilised for example by Audi for welding the longitudinal roof joint on the A4 model. However it is not reliably achievable on suspension applications which utilise thicker sections. These would require more force to close together than is feasible with the roller technology. Lasers may be applied to Aluminium applications, but more issues arise than with steel (12). Despite recent advances in efficiency with pumped laser technology, laser applications still suffer high capital, maintenance and running costs in comparison with other joining technologies. Laser is not considered further due to capital cost, robustness and requirement for accurate assembly tolerancing.

Laser Welding with filler wire In principal the same technology as the above autogenous process, but with the addition of a filler wire system similar to MIG. This advance reduces the requirement to have 'perfect' fit-up, but adds further capital cost, wire consumable cost, control, maintenance and running costs to an already potentially expensive option.

Electron Beam Welding This is also an autogenous process. Often performed in a vacuum chamber. It has been utilised for elements of chassis welding, particularly in the USA. It is now largely superseded by more recent technologies.

Ultrasonic Welding Ultrasonic Welding for Advanced Transportation Systems by Feng (13) concentrates on materials of autobody thickness. The process is considered as a variation of FSW, which will be discussed in Chapter 4. The Sonotrode, operating at 20-40 kHz with amplitude 5 to 50 micrometers, causes minimal relative motion at the interface. Mortimer (14) shows that ultrasonic welding is favoured for aluminium body sheet applications, but it is unclear if this would translate to heavier chassis sections. As with FSW, Ultrasonic Welding is currently more applicable to aluminium than steel, also to thinner materials, and is not yet applicable to thicker chassis applications.

3.2.2 Non-Fusion Joining Technologies

Brazing - including laser brazing Brazing was formerly considered only as a craft technology utilising a gas torch, but now has volume production automotive applications, particularly when utilising a laser as the heat source. It has become a viable option for body in white applications and less severe structural applications. A typical utilisation may be the fixing of a mounting bracket to the body bulkhead. The advantage is that the bulkhead would not have to be pierced, keeping noise, heat and fluids from the cabin. The downside, for higher strength safety critical structures, is that there is no intimate mixing of the metals to be joined; the joint relies on a surface bond which is relatively easily contaminated prior to application of the braze, this producing an unreliable joint. It is currently considered insufficiently robust for chassis applications.

Self-Pierce Rivets Self pierce rivets are a mechanical alternative to welding, and may be seen particularly as an alternative to spot welds, being located as single discrete points in the structure. The rivet is pierced into, but not through, the second or subsequent layer of material. As with spot welds, they are mostly utilised for body thickness materials, and have also been utilised for aluminium body structures, for example in recent vehicles by Jaguar, but may also be viable for slightly thicker materials. They have found applications in automotive seat structures, where the possibility of potentially harmful galvanic corrosion between the aluminium and the normally steel rivet material is not an issue. The process requires access to the reverse side of the joint for support. They are utilised primarily in aluminium applications, occasionally in steel. They are progressing into applications with high loads, vibrational inputs and safety critical requirements, and may be adopted for chassis applications in conjunction with adhesives. The cost of each rivet counts against the process when compared with non-consumable welds.

Self Pierce Rivets are the selected methodology for body assembly of Jaguar's current aluminium vehicle range. Mortimer (14) outlines Jaguar's plan to further lightweight the body structure. Laser, FSW and Ultrasonic welding are considered as alternatives: adhesives alone are not, due to cycle time requirements. Cold processes are preferred to eliminate distortion. For aluminium, FSSW (Friction Stir Spot Welding) is seen as providing a joint 90% as efficient as a fusion spot weld. Improvements in aluminium material elongation are seen as an enabler to produce larger pressings in order to drive down weight and cost.

Adhesive Bonding Adhesive bonding is again an alternative to welding, and may be utilised where flat surfaces may be designed-in to provide sufficient joint area. The normal failure mode is Peel, and joint designs must guard against this. Potential applications are numerous in body-in-white assembly, and joints of sufficient strength may be achieved in chassis applications, but concerns remain with regard to long term joint integrity in fatigue-sensitive suspension applications situated in a corrosive environment such as that found underneath a vehicle. Not considered further here due to process robustness issues.

Adhesive bonding supplementary to other methods To respond to issues incumbent in individual mechanical and chemical joining technologies, various combinations of these technologies have been proposed. One weakness of adhesive alone, the Peel Strength, is considerably improved by the presence of a rivet or other local fixing, and this is a solution adopted by Lotus, Jaguar and others for body-in-white assembly. Despite the additional security from the rivet, there remains some lack of confidence in the application to suspension systems.

3.3 Material Considerations

Automotive suspension components are primarily manufactured, usually pressed, from steel. Steel has adequate strength in relatively thin sections, is easily formed and cost effective. However it requires surface treatments to achieve satisfactory protection from corrosion, and is relatively heavy. Modest steel compositions are usually specified, as this permits the complex drawn profiles to press without tearing, and the low carbon equivalence minimises weldability issues. Higher strength steels may be specified to achieve lightweight applications, but bring increased restrictions on form and may lose the majority of their enhanced properties when welded. New grades of steel seek to provide increased benefits by, for example, producing steel with sufficiently formability to allow complex parts to be produced, but in the process to be work hardened in order to produce an acceptably high strength in the finished part.

Amongst its competitors, only Aluminium has made significant inroads into the dominance of Steel in this area. It was introduced initially at the upper end of the market, initially for high performance vehicles. In these applications the aluminium is usually forged. This process maximises the potential of aluminium, providing lightness with strength, but at a high price. Cast, sheet and tubular aluminium designs have also been utilised. Recycling cost must also be considered when selecting lightweight materials. Aluminium requires less energy to recycle due to its lower melting point, but it can be more sensitive to grade separation issues. Price volatility remains a significant issue with aluminium, and if a large-scale transfer were to occur, the laws of supply and demand may render the option uneconomic at current output.

3.3.1. Steel If Specific Steel Welding issues for lightweighting applications are considered, the primary disadvantage is the loss of the beneficial properties conferred by high strength materials at the weld. As the weld is usually compelled by geometrical and manufacturing constraints to be at a high stress location, the increase in strength in the remainder of the component may be irrelevant if the component will fail at the weld in service. Any cost incurred in specifying a higher strength material would be in vain. Spot welding shares the above concern, but as spots are surrounded by un-welded material and are not immediately at extreme edges of components, the detrimental effects may be reduced.

Lightweighting Technologies for Steel

Tailor Welded Blanks The current technology is to purchase steel on a coiled roll which weighs several tonnes. The steel is de-coiled and run through a blanking press which presses out a flat blank of complex circumference but of fixed uniform thickness. It is likely that to fulfil its designed function, the blank need not be so thick over the entire surface, the blank thickness being determined by the single highest stress point. If the high stress covers a high percentage of the surface, then little is lost by being restricted to a single thickness. If, however, much of the section is under-stressed then the application may be suitable to be considered as a tailored blank (15).

One example of this in body fabrication is a door skin pressing. Most stress occurs along the vertical hinged side of the door which would be designed with greater thickness or higher mechanical properties than the remainder.

A tailored blank is usually supplied as a flat rectangular sheet, with dimensioned width and length to suit the finished component size, plus allowances for the pressing operation. The tailored blank consists of two or more pieces; each may vary in thickness and/or mechanical properties. The intention is to provide only the properties that are required to fulfil the design requirements at the locations that they are needed, with reduced functionality at lower stressed locations. The sections are joined, usually now by butt laser welding, although other technologies such as mash seam welding are available. This clearly offers opportunities to lightweight and to use less expensive steel grades where appropriate. Against this clear advantage are a number of restrictions and issues which need to be considered: The difficulty of both modelling and practically press forming the component is increased with the non-homogenous properties of the tailor welded blank.

The laser welded joint has residual stresses not present in the plain sheet and may act as a fatigue initiator; this is exacerbated if a change of section thickness is also co-incident.

The supplied condition of the blanks, as flat sheets, is not as efficient as the long coil of the standard material. Effective material utilisation is a critical cost factor, and the ability to 'nest' profiles together both along and across a coil is vital to improve material utilisation and reduce the percentage of wastage from each coil. The requirement to provide tailored blanks as a discrete flat sheet significantly restricts the ability to 'nest' components, (maximising 2D component yield from the coil by optimally condensing blank profiles), and therefore generates a cost barrier to the widespread adoption of the technology.

Steel Tailored Blank technology is a valid light-weighting technology which functions optimally when there are significantly different property requirements in various areas of the component, and where the loss of nesting opportunities compared with a standard coil does not generate an unacceptable cost burden. Further work is required in this area by steel suppliers to maximise the advantages of the technology whilst minimising the downsides in accordance with the limitations advised above.

Steel Surface Technologies The suspension system operates in a harsh environment, subject to simultaneous mechanical and chemical attacks on the paint finish from stone chipping. Once the paint film is breached, corrosion will initiate and remove adjacent paint protection by creeping between steel and paint. Paint technology has improved significantly in recent years in both durability and environmental acceptance. The increased life (to 960 hours salt spray resistance) is now an industry norm.

Maintaining Corrosion Protection for Thinner Gauge Steel The surface protection provided to protect the steel from corrosion, despite advances in paint technology up to the current 960 hours salt spray resistance, still suffers in the harsh environment surrounding the road wheels. This would be an increasing issue for thinner steels. The ensuing corrosion not only reduces the through thickness of the steel over time, but, more significantly, localised crevice attacks take place, generating stress raisers which result in preferential fatigue sites which then initiate crack growth (corrosion fatigue) and may consequentially reduce the service lifetime significantly.

Zinc Mill-Coated Steel To discourage the failure mode observed with paint, some customers specify their steel with a thin layer of coating, or galvanising, usually zinc based (16). This is added as a finishing operation at the steel mill or rolling mill. A zinc coating, being less noble, (whether Mill or Hot Dip applied) will continue to protect the steel by corroding preferentially, even when physically breached. Mill applied coatings are a partial benefit for the durability of the component, coating and protecting perhaps 95% of the surface area of the finished component, This coating is effective, but is not present on the sheared edges of the component after pressing, and is also removed by the MIG or spot welding process during fabrication. Unfortunately this results in the coating being absent from the two areas of the finished component which usually most need to be protected: the edges and the welds.

The removal of the zinc during welding may also cause porosity in the weld, as the zinc, with a boiling point lower than the melting point of steel, bubbles through the molten weld metal, some being entrapped upon solidification and hence producing porosity as bubbles in the solidified weld. This detrimental effect is partly a function of joint design, and partly a function of welding speed. If the joint may be designed without entrapment areas, and the welding speed varied to permit the zinc to bubble away prior to weld solidification, then the problem may be minimised.

Hot Dip Galvanising Hot Dip Galvanising differs from the above as the completed fabrication is coated in a zinc-based alloy by submersion. This coats edges and welds to avoid the issues of the mill-applied coating, but the coating thickness is less controllable than the mill operation, and higher coating thicknesses of 30 to 90 microns are typically applied. This would add weight to a suspension component of the order of 5 to 10%, which is not immediately attractive when in pursuit of weight savings. New hot dip galvanising processes are available (17) claiming similar protection with a more uniform coating of typically 15 microns, such as MICROZINQ D4. There are, however, unique attributes of the hot dip galvanising process which offer potential to support lightweighting opportunities:

Hot Dip Galvanising Corrosion may result in improved corrosion protection. If high strength steel is specified for lightweighting purposes then it will necessarily be of a thinner gauge to realise the lightweighting benefits. Any corrosion effects reducing the effective thickness of this steel will have a commensurately detrimental effect on durability, and it may be necessary to protect this thinner section with a full zinc protection coat. This could result in an overall weight saving, whilst maintaining or improving the corrosion performance.

Hot Dip Galvanising may result in a beneficial reduction in residual stress in the component. The paint process heats components to approximately 200° C, whereas the hot dip galvanised bath is maintained at 500/550° C. As there is some evidence of distortion of fabrications during the galvanising process, there may consequently be a corresponding reduction in residual weld stress. A reduction in residual weld stress may result in a thinner material thickness and a consequential weight reduction.

The soldering effect provided 'automatically' by hot dip galvanising may improve several performance metrics of the design. Many automotive suspension components consist of overlapping pressings spot-welded together. Sufficient welds are provided to transmit the required forces between the pressings, but the areas between the spot welds are unsupported and the stiffness and strength of the component is limited.

Hot Dip Galvanising may also be considered as a soldering process. In addition to coating the surfaces, the molten zinc is pulled into the gaps between the pressings by capillary attraction, where it solidifies and solders the panels together. The process will bridge small gaps between adjacent plates and provide an effective soldered joint as it is also supported by the spot welds. This can have major beneficial effects on the stiffness and strength of the design, improvements of 40% in stiffness are realistic, and may permit a considerably thinner material section to be specified if stiffness was the design constraint. The number of spot welds may also be reduced.

3.3.2 Aluminium There are specific aluminium welding issues for lightweighting applications. Aluminium differs in many ways from steel in its response to MIG welding. Initially, the oxide layer must be overcome before fusion may occur. This requires consideration of polarity and ionisation to eliminate the oxide with the arc immediately prior to welding. Consideration must be given to the heat input requirements determined by the opposing issues of a higher thermal conductivity, which carries heat away from the weld, and lower melting point of aluminium. Control of porosity is also a much greater problem in aluminium than steel due to the lower material density.

The consumable welding wire must be carefully matched to both materials being joined. If more than two material grades are joined in one cell then different wires (and therefore additional robots) may have to be specified, with a consequential capital cost increase. Aluminium is less tolerant of fit-up gaps. Increased costs are incurred in ensuring that fit- up gaps are minimised. As the coefficient of thermal expansion is greater for aluminium, post weld distortion may be increased, and the need for tight fit-up conditions exacerbates the effects of the higher levels of distortion which will occur during the welding sequence.

The reduction in fatigue life caused by the presence of a weld, compared with an un-welded coupon of the same dimension, is more severe for aluminium than for steel. This lack of a significant fatigue limit, below which fatigue will not occur, is a fundamental limitation of aluminium in fatigue applications such as suspensions.

It may be summarised then that aluminium in extruded form may appear to be a suitable material and manufacturing process respectively for lightweight suspension component, but that MIG technology may not be suitable for adoption as the fabrication process due to its limitations. An alternative welding process to MIG is required to progress the aluminium option, and there is a need to review all the relevant current fabrication technologies to find the most appropriate technology.

3.3.3 Other Materials It is necessary to consider other current potential suspension materials and new materials under development. Whilst principally steel, and secondly aluminium, are the primary materials utilised in suspension applications, others have been considered and deemed to be requiring further development. A review was initiated to determine the suitability of other materials for chassis utilisation.

Carbon Fibre Utilised where costs is less of an issue and ultimate strength and stiffness to mass ratio is paramount (18). The material properties are uni-directional for an individual sheet; this permits very efficient designs where a near-unidirectional load input is required. Multiple thicknesses are required to achieve multi directional properties. Joining is not usually a requirement. The component is laid-up to the finished profile before autoclaving.

Carbon fibre is therefore acceptable for suspension wishbones for Formula 1 cars, where suspension loads are well documented, lightness and stiffness are paramount and cost is secondary. For road use, the risk of fracture from an isolated high load condition, risk of fatigue initiating damage from debris impact and cost reduces its potential as a dynamic chassis component material.

Composite Materials Composites generally share many of the structural advantages and limitations of carbon fibre, but at a reduced level and with reduced costs. They have the advantage of being isotropic if required, and mouldable to shape, but low bulk strength often determines a bulky design which is difficult to package. Composites do not accept high point loads easily, and strengthening metallic inserts must often, as a result, be provided at these locations. Impact performance may also be a limitation, especially since crash management issues have assigned increasing responsibilities to the performance of the dynamic suspension components. Material costs are intrinsically competitive, but long cycle times are required during the manufacturing process which leads to high capital investment, this increasing the piece cost, often to an uncompetitive level.

The Perfect Material If, having reviewed the possibilities and limitations of the current materials, the question is inverted to ask which material could be specified, if everything were possible. The answer may be useful in defining future development directions. If a suspension arm is taken as the example, the following specification would be ideal: to be formed in one piece, without joining, with minimal capital machine requirement costs, to have a solid outer shell to form a weatherproof skin and to provide maximum material density at the outer edges of the profile to give the maximum second moment of area, to have an interior filler material of a honeycomb construction, graduated in density from almost solid just under the skin to almost 100% air at the centre, and not to require surface finishing for corrosion protection.

Care must be taken not to take the analogy too far, as structural self generating and healing properties are optimistic for near-future structural automobile applications, but the principles listed above are valid in the search for the perfect part. If new technologies are examined which approach these ideals, then there are some engineering materials which are moving closer to the 'skeletal bone' ideal, candidates such as Metal Matrix Composites.

Metal Matrix Composites (MMC's) For automobile structural applications, this principally means Aluminium MMC's on the grounds of cost, and the ability to be formed on conventional casting equipment. The aluminium is the matrix of the

MMC; other MMC matrix materials are available, such as Titanium, Magnesium and Copper. The matrix is reinforced with either continuous or discontinuous fibres, whiskers, particulates or wires. Wires are metals, the remainder are ceramics. For aluminium applications, the most relevant MMC's are: Continuous Fibres: boron, silicon carbide, alumina, graphite. Discontinuous Fibres: alumina, alumina-silica. Whiskers: silicon carbide. Particulates: silicon carbide, boron carbide.

The primary advantage of MMC's is the ability to tailor the mechanical properties. Monolithic metals tend to be isotropic, with minimal directional variation in properties generated by processing effects such as rolling. This directionality may be considered in suspension components, particularly with regard to fatigue. MMC's may have significant beneficial anistropic properties designed in, depending upon the type, size and orientation of the reinforcement. A paper by Marzoli (19) investigated the Friction Stir welding of an Aluminium alloy reinforced with 20% alumina particles, extruded then T6 treated. The paper concluded that high joint efficiencies could be obtained, with failures outside the stir zone, by utilising process parameters established for un-reinforced materials.

Particulate and randomly orientated whisker reinforcement tends to remain isotropic. Reinforcement with longer fibres will produce greater strength and stiffness in the direction of the fibres. Beneficial residual stresses may be engineered into the material as it cools, perhaps to give a compressive preload to help offset a tensile peak load in a suspension kerb strike event, for example.

The ability to vary strength and stiffness of a suspension component directionally gives the designer benefits which are not possible with conventional monolithic materials. Provided these advantages are understood and properly applied to the component, these material advantages may be translated into real weight reductions, possibly in conjunction with improved dynamic behaviour through controlled asymmetrical compliance.

MMC's are often produced by casting technology. Whilst this is traditionally more expensive than a pressed and welded approach, one advantage of this is that complex suspension components which are usually of welded construction may be designed in one piece, with details such as brackets and fittings being moulded in. Therefore the need to join MMC's to arrive at a final design is reduced. Welding may also be reduced or avoided by the use of extruded MMC's. Fabrication of MMC's is in its infancy, but conventional welding techniques are available. Table 3 indicates a matrix of suitability to weld different forms of MMC's.

Table 3 - Comparison of Welding Techniques for MMC's by AZOM

	Form of MMC		
Process	Sheet	Extrusion	Casting
TIG	good	good	good
MIG+	good	good	good
Resistance	fair	n/a	n/a
Laser	poor	poor	poor
Electron Beam	poor	poor	poor
Friction Welding	n/a	good	good
Diffusion Bonding	fair	fair	fair
MIAB*	n/a	fair	n/a
Flash Welding	n/a	good	good
Brazing	fair	fair	fair
Adhesives	good	good	good

+ = metal inert gas welding, * = magnetically impelled arc butt welding

In the future, for many of the same reasons that Linear FSW is attractive as a technology for welding Aluminium, particularly in extruded form, FSW may also be the fabrication technology of choice for MMC's

4.0 Friction Stir Welding

4.1 Introduction to Friction Stir Welding (FSW)

Friction Stir Welding was invented at the Welding Institute in the UK in the early 1990's. Linear FSW is a process similar to vertical milling, with a rotating tool traversing a joint line. As Figure 10 indicates, a shoulder on the tool is in contact with the weld and under vertical load, which heats the material to a plastic, but not a molten, state. The tool is partly immersed in the weld, and the rotation produces mixing of metals from both sides of the joint line. On cooling, the material is joined, without a heaped weld profile. No consumables have been utilised, and many of the detrimental effects of molten-state welding, such as distortion, have been eliminated or minimised.

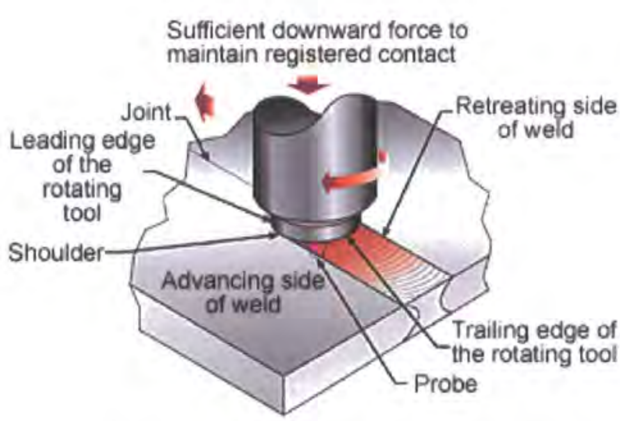


Figure 10 - Friction Stir Welding by TWI

The technology has more in common with a machining operation than a fabrication process. Temperatures are moderate, spatter and fume are eliminated, and virtually all environmental issues are greatly improved. The process variability of the technology is minimised, and the lack of a heaped weld profile reduces weight and the stress raising effect as the surface is flat, with no stress raising discontinuities.

FSW does require that the friction generating force is reacted, which generally means that access is required to both sides of the workpiece. This may be avoided with a bobbin tool which is assembled through a pre-drilled hole, but this is only viable for long welds. For aluminium, FSW is a viable option. For steel, the greater temperatures required mean that tool materials are currently very expensive, currently limiting economic acceptance.

In the same way that addition to Linear FSW challenges conventional MIG welding, Friction Stir Spot Welding (FSSW) challenges conventional spot welding. The technology utilises a similar rotating tool, but instead of traversing it is plunged into the weld as with a conventional spot weld approach. Again reaction force must be applied, and improved tool materials are required for harder materials to be joined, but production viability for steel, particularly high strength steels of certain compositions, may be viable at prototype level.

4.2 FSW Applications in the Automotive Industry

Change Management Any change to an entrenched industry based one specific material and manufacturing method would represent a Disruptive Technology. Jones (20) refers to Friction Stir Welding specifically as a disruptive technology in that it overcomes limitations of current technologies whilst also greatly reducing cost. It cites the figure of 20% of construction costs of a supertanker being attributable to control of welding distortion, a problem which FSW minimises.

In seeking to advance assembly of aluminium for automotive use, aerospace technology, with a history of aluminium assembly development, may be a useful reference. Webb (21) advocates flexible rather than dedicated robotics in recognition that tolerances and distortion are best controlled with an approximate system for robotic pick and place purposes. This is then overridden by non-contact metrology control to overcome the inherent distortions and misalignments to provide a robust system.

Toyota is a world leader in the development of automotive technology, and their design and development processes are much imitated by competitor organisations. The introduction of a new suspension system may benefit from an understanding of a net-based concurrent Engineering (SBCE) system from Toyota (22). The principle is to embrace a wide initial selection of possible solutions, then move quickly through elimination to adoption and production. In comparison with other methods, which reject imperfect ideas early, several options are developed beyond the initial stage. Toyota believes that the lessons learned from this exercise are worthwhile even if they emanate from the solutions which are not immediately progressed for the current model under development.

Any new suspension component technology will have to match or exceed the in-service loads of current technologies. Initial optimisation of the design strength, stiffness and durability will be obtained by a finite element analysis. Lee (23) compares the structural performance of a one piece cast aluminium suspension arm design to a pressed steel arm, using a topographical optimisation approach. Currently, FSW processes are generally optimised by an iterative approach, or at best a Design of Experiments method. Work is progressing to develop simulation tools to model FSW processes. Reddy (24) describes the approach taken by Altair Engineering to utilise a finite element code to resolve the mass, momentum, and energy conservation equations generated by FSW. Model predictions are claimed to be within 10% of experimental data. The prediction of temperature distribution, forces, moments and tool torque is also possible.

FSW Automotive Joining Processes The issue of applying aluminium to automotive subframe structures was discussed by Hinrichs (25). The slow speed of GMAW (gas metal arc welding) of aluminium was cited as a barrier to wider aluminium adoption, as was the need to pre-clean the surface. Other downsides were identified as unreliability and flaking of the wire, leading to blockage of the wire feed system and consequent burn-backs. Conversely, two weld types were completed by FSW for which no consumables or pre-cleaning of the surface was deemed to be required.

A range of innovative joining processes were reviewed by Kallee (26). The centre tunnel of the Ford GT (GT40) is FSW'd aluminium, as are some suspension links for Lincoln Town Cars. These are fabricated from two identical extrusions; simultaneously FSW'd from both sides to provide a full thickness weld. However, it is not immediately apparent why the full component was not manufactured from one extrusion, as the maximum dimension fits within the permitted diameter of current extrusion technology. This is investigated in Chapter 6. Also referred to by Kallee (26) are the following: Mazda are utilising FSSW (Friction Stir Spot Welding) for auto body applications to avoid spatter and reduce energy consumption, Dan Stir is FSW'ing cast or forged wheel centres to wrought rims to reduce weight by 25%, Sapa produced an FSW aluminium engine cradle at 16kg against 23kg for the original steel component.

To determine changes in joining methods within the automotive sector, it is helpful to view equipment sales figures. As robotics play a key role in many automotive joining processes, sales of relevant machines and their intended purpose are especially informative. Young (27) provides such data, breaking down UK robot sales to market sector and application. The salient figures for our purposes are that, for 2004, the two dominant applications, arc welding (84 new) and spot welding (188 new) have reduced by around 45%. However, applications for 'dispensing, sealing and gluing' (50 new) represent an annual growth of 80%. Almost all of these new machines were for automotive applications. This is in line with observed changes in the UK automotive manufacturing base, with a movement by luxury and sporting marques to adopt adhesive and self pierce riveted aluminium bodyshell construction in lieu of spot welded steel.

4.3 FSW Applications in other Manufacturing Sectors

The potential for FSW in automotive suspensions may be partially assessed by seeking evidence of progress in other industries, especially transport sectors.

Rail The need to lightweight is pertinent to the rail industry, as is the need to improve crash performance. Carriage construction techniques have now been developed to utilise extruded aluminium panels which are linear friction stir welded along the length of the carriage. This is an ideal application for Extrusion/FSW technology, rewarding FSW's reduced distortion capabilities and offering long weld lengths to minimise FSW's stop/start issues.

Shipbuilding Ship decking and superstructures are increasingly moving to aluminium in lieu of steel for lightweight, corrosion and stability reasons. This has permitted FSW of extrusions to gain a foothold in this market. Production of ribbed decking sheets from T profile aluminium extrusions by Marine Aluminium of Norway is one of the first production FSW applications. FSW is also viable for aluminium hulls; steel hull construction awaits only improved FSW tooling before it may be considered viable.

Aerospace The utilisation of FSW for aluminium fuel tank construction for Delta II and Delta IV space launch vehicles was an application using thicker material sections than usual for automotive utilisation, but it proved the technology in a high visibility application.

Aeronautics Aeroplane technology is often considered to be at the forefront of technical achievements. Yet in terms of joining technology, the majority of developments of the last century have been largely ignored by the industry. Ship construction evolved from riveting to welding early in this timescale; yet riveting, often now supported by adhesive, is still the predominant aeroplane construction technique for fuselage construction despite the exponential growth in labour costs which this technology demands. For landing gear, where a fabricated design would seem to be the natural way to incorporate features such as brackets and lugs to attach wheels, hydraulic actuators and fixings; complex forgings are predominantly utilised which incorporate these features in a one piece design at an high cost penalty. It is noted that fusion welding technologies, adopted by virtually all other sectors, has been generally overlooked by the aircraft industries in favour of mechanical fasteners.

There are several reasons: Cost is less of an issue here; aluminium is the predominant material; reparability is easier with rivets and joining distortion is virtually eliminated, but the primary issue is arguably one of fusion welding process variability coupled with detrimental effects on metallurgy, together undermining confidence in the durability of a fusion welded product in a high-risk environment.

All current fusion welding techniques have many input variables, this necessarily results in high output variability of the weld performance; to a lesser extent in terms of strength and a greater extent in terms of fatigue. For a product where factors of safety are limited by weight constraints, low variability processes are mandatory. In order to ensure that the worst combination of a high variability fusion welding process will still result in an airframe of satisfactory durability, the mean thickness of components must be increased to dimensions higher than that required to support riveted construction. The joint efficiency of the riveted joint may be theoretically lower, but when process variability, weld profile and detrimental metallurgical effects of the welding process heat are considered, fusion welding would add mass through process variability, and therefore riveting has remained the process of choice.

Only recently has a welding technology become available which this industry has considered as a viable option to riveting. This process is Friction Stir Welding. The relevant technology is discussed in Section 4.4, FSW of Aluminium, later in this Chapter, but for the aeronautical industry the advantages include reduced detrimental metallurgical effects, high process repeatability, and a flush weld profile.

The new Eclipse 500 business jet is predominantly Friction Stir Welded. The cost of the twin-engined jet is projected to be less that $1 Million, or one quarter the traditional cost for a 4 to 5 seater executive jet. The business plan made possible by savings of this magnitude will see a fleet of Eclipse 500's operating between smaller municipal airports, initially in the USA. The principal cost reduction was the replacement of the 7000 fasteners which would have been required for traditional construction with 263 friction stir welds.

The Relevance of Bicycle Frames At first sight the cycle industry would appear to have little to offer in this technical evaluation, but the construction of a cycle frame is not dissimilar to an automotive subframe, and both are designed against road induced loadings and environments. Also, whilst the industry may not enjoy the development budgets of their automotive peers, their customer's are effusive on the subject of efficient frame design, having to propel their products utilising their own efforts; this placing considerable pressure on frame manufacturers to produce lighter designs which still offer adequate durability.

There are few opportunities in the automotive arena to compare back-to-back products such as subframes, as suspension components and systems are designed in close co-operation with customers, and are unique to the architecture of each model range. Bicycle frames do provide this opportunity to compare, as most mainstream cycle frames fit into a type profile (Racing, Touring, Off-road, Downhill) and within each of these sectors a sales battle has been ongoing between comparative steel and aluminium designs. An analysis of this conflict is useful to our understanding of steel and aluminium design issues for application to automotive suspensions, although it must be considered that aluminium does not figure in extruded form, and friction stir welding has currently not been adopted by the cycle industry.

The fundamentally triangular form of a frame is constructed from three primary tubes. Early frames utilised three steel tubes of identical section, brazed into hollow fittings (lugsets) at each corner. Steel frames have developed over time by utilising alloy steels; developing different diameters to suit the loading conditions and butting the tube material (reducing the wall thickness in the central section of the tube only)

For off-road cycles, larger diameter tubes were required for strength. Often the lugsets traditionally used to reinforce the corners were neglected, and the tubes joined directly using welding. This was used in preference to the brazing which had been adequate in conjunction with the lugsets. As a result of this strengthening, steel off road frames were considered heavy, and aluminium was introduced to save weight.

The status quo today is that aluminium frames are of similar weight but slightly more expensive than steel. From a review of comparative tests in technical trade literature, one opinion which does prevail is that aluminium frames feel stiffer to ride. This is initially surprising, given that aluminium exhibits only one third the stiffness of steel and extrusions are not specified, which would be capable of achieving this stiffening effect. The understanding of this paradox is directly relevant to the development of automotive subframe technology. Given that both the steel and aluminium frames are of lugless construction (tube welded directly to tube), the aluminium tube would have increased wall thickness and diameter by design to compensate for reduced strength and stiffness compared to steel. The design would be stiffness limited at this stage.

The frames would then be welded up and tested. During the frame fatigue test, it would be found that the aluminium frame would fail by cracking from a weld at a fraction of the cycles of which a steel frame was capable. The designer would be compelled to increase the aluminium material thickness or diameter (usually the thickness) incrementally and re-test until a satisfactory fatigue life was achieved..

The additional material which he would add, being much lighter than steel, would not make the weight of the aluminium frame uncompetitive against steel, but would increase the stiffness above the initial target, hence giving rise to the road tester's comments that an aluminium frame feels stiffer to ride. The reason that the designer would be compelled to add weight is that aluminium is more detrimentally affected than steel by fusion welding, as explained by Maddox (28). This is supported by warranties offered on frames, typically 2 years for aluminium, and 15 years for steel.

So the weight and cost; the two principal parameters of frame design, could, for aluminium, be simultaneously reduced to the limitations imposed by the initial stiffness constraints if only the welding process would not have such a detrimental effect on aluminium alloys.

From the above, it may be concluded that friction stir welding, which minimises the detrimental effects of welding, in conjunction with extruded aluminium which has the ability to increase stiffness through section optimisation, but they are not particularly easy to apply to a tubular cycle frame structure due to its weld joint configurations. However, to return to the automotive suspension applications, FSW and extrusion technologies are able to be applied to a sympathetically designed subframe structure where suitable weld geometries may be incorporated and the above benefits may be brought to bear. This design would be the ideal combination, and potentially offer the fatigue life and stiffness of the heavier structure in conjunction with the cost and weight of the lighter structure.

4.4 FSW of Aluminium

Whilst aluminium extrusions offer great advantages in part integration and therefore reduced part count, Benson (29) notes that automotive applications seldom offer the opportunity to utilise extrusions in the straight form, and that bending or hydro-forming are usually required. A suspension frame assembly was produced with cast, plate and extruded elements, but with predominantly MIG welding.

Tool design must be optimised to obtain adequate stirring of the aluminium and to avoid premature failure due to discontinuities. Ericsson and Sandstrom (30) compared the effect of different tools on aluminium lap joints. It is noted that the formation of 'hooks' and associated notches on the advancing and retreating sides of the tool may lead to detrimental fatigue and tensile strength performance. Optimisation of tool geometry and selection of travel relative to advance/retreating tool direction is important. Overall, overlap FSW weld geometry was found to be much worse (25% efficiency against 90%) than a butt weld. From this example, a butt welded joint design was determined for the design developed later.

The majority of Friction Stir welding performed to date has been with a single piece tool. The metal under the shoulder may overheat as the shoulder is travelling faster than the tip for the same rotational speed, and generates more heat. If the pin and shoulder were separate they could be rotated at different rotational velocities, or even directions, providing greater opportunities to optimise performance. The experimental work by Watt (31) arranged for the shoulder to rotate from approximately 27 % less than the pin in the same or opposite directions. One potentially useful conclusion for counter rotational operation in automotive applications is the reduction of process torque due to the self cancelling effect between the two rotating elements. This would reduce the reaction loads which are a significant limitation in robotic FSW.

In a paper advising of further FSW trials at TWI, Thomas and Sylva (32) described Re-Stir, which eliminates weld asymmetry by reversing tool rotation periodically.
Also Com-stir technology is reviewed. This superimposes an orbital motion over the usual rotation, permitting wider weld paths and improved surface oxidation

fragmentation. A Self-reacting tooling (Bobbin) approach was developed for welds such as hollow extrusions where it is difficult to provide the vertical reaction force required. The self- reacting tool is two-piece, utilising a separate long pin with a reaction boss built in.

Linear FSW generally provides for only X and Y movement, with only fine weld control variation in Z direction (vertical). This is sufficient height to control the depth of the tool relative to the top surface of the weld. However, for some welding applications, for complex geometries, coarse Z control is required to follow the undulating contours of the material topography. Adopting FSW to mount robotically is theoretically an interesting solution. Smith (33) discusses the development of such a system. It was found that force control gave more stable results than displacement, and with hydraulic rotational motors in place of the original electrical ones, satisfactory welds were made.

Friction stir welding is considered as a stable process with less inherent opportunity for defects than fusion welding processes. However the process is relatively new and unproven in high volume applications and potential defect types must be identified, understood and controlled. Bird (34) defines flaws pertinent to FSW in aluminium, and the two flaws which are particular to FSW, Joint Line Remnant (JLR) and Hook Flaws are identified. The paper also discussed flaw consequence, as related to mechanical test results.

One of the first applications of aluminium linear friction stir welding to a body structure is on the Ford GT (GT40). A double opposing head FSW machine welds both sides of the transmission tunnel for a length of approximately 1m. This area has to be strong and rigid both to oppose the beam stresses in the bodyshell and to protect the fuel tank in crash, it being located in the transmission tunnel. Bloss (35) concentrates on the body chassis structure holistically. The primary structure is aluminium extrusions, with a thin wall casting arrangement for the rear engine gearbox and rear suspension mountings. The parts list for the body/chassis structure comprised 35 Aluminium extrusions, 7 complex castings, 2 semi-solid formed castings and several stampings. The structure was robotically fusion welded, around 450 welds were required, with vehicle side to side inter-weld cooling stages to minimise distortion. Also featured were designed-in panel mounting locations which were machined post welding to achieve dimensional accuracy.

Metal Matrix Composites (MMC's) of cast construction may avoid the need to be joined to a limited extent by careful integration of features into the cast profile. However some applications will require the composite to be joined. The multi-phase construction and anisotropic propertied may be expected to render any joining process challenging. Ellis (36) reports on early attempts to focus known welding/joining technologies onto MMC fabrication. The conclusion was that new challenges were set by these materials, and many existing joining processes suitable for monolithic aluminium were not suitable for MMC. It was too early in the development of FSW for it to be included in this trial.

A later paper by Storjohann (37) re-visited the above approach, comparing the fusion welding processes of Electron Beam, Gas Tungsten Arc and Nd:YAG laser for MMC application. These were compared with the maturing Friction Stir Welding approach. It was found that the fusion welded components developed either very hard or very soft regions within the weld metal. Either of these would limit performance of the component. The Friction Stir welded components enjoyed a homogeneous microstructure with a uniform hardness profile, which would be expected to be an improvement over the performance of the fusion welded components.

4.5 FSW of Steel

The feasibility of extending FSW from aluminium into steel was explored by Thomas (38). The FSW process relies on the tool material having a significantly higher melting point than the process materials. This is easy to achieve for aluminium, considerably less so for steel. In the steel trials, the tool ran at a bright orange colour; over 1000° C. Tool wear therefore is significant, and limiting currently for production purposes, but prototype work is feasible. Significantly, 12% chrome steel materials are in many ways easier to FSW than carbon steels. This may permit higher strength steels to be utilised for light weighting purposes against the lower strength steel currently selected for their ease of fabrication with MIG welding.

The mechanical properties of Mild Steel FSW joints were examined by Hirakawa (39). The trials were progressed with mild steel of 12mm thickness, butt welded from both sides simultaneously with tungsten tools. Welds made with tools remaining co-axial were successful, with mechanical tensile tests failing remote from the weld.

Shipbuilding would be one industry to benefit greatly if FSW of steel could be productionised. DH-36 steel is utilised in shipbuilding applications and Lienert (40) reported on trials on material of 0.18 inch thickness. Wear trials showed that tool dimensions were unaffected by welding the 36 inch long samples. Small defects near the bottom of the stir zone were believed to be resolvable with tool modification, and mechanical testing results were acceptable.

To progress with FSW for steel, tools better able to withstand the combined temperature and abrasion effects are required, and research is progressing in these fields. PCBN (Polycrystalline Cubic Boron Nitride) is one such material. Others are investigating DLC (Diamond-like Carbon-Polymer-Hybrid coatings), Silicon Nitride and Tungsten Rhenium. Kiuru (41) describes the progress of FSW tool developments.

FSW of advanced materials, including steels, are discussed by David (42). Recent tool advances at ORNL (Oak Ridge National Laboratory) have produced Tungsten based and Iridium based tools which are claimed to successfully weld steel. However, tool life and cost hurdles would still have to be overcome for production.

There are opportunities in automotive applications when aluminium is required to be attached to steel. This is difficult for fusion welding due to the different melting points. With FSW being a plastic phase process, opportunities may exist to succeed. Fukumoto (43) describes experiments to butt weld steel and aluminium. A point was found where the tool was rotated almost 100% in the aluminium, with only 0.05mm interference into the steel. Only this interference condition could give an effective weld; any more interference into the steel would break the tool.

4.6 Development of the Research.

Aims and Objectives

The aim is to research the requirement for lightweight vehicles and to understand the special limitations and benefits which apply to suspension components in particular. Then, recognising that lightweight materials are available for these applications in acceptable volumes, why greater use is not being made of them. This implies that there are technical roadblocks to the increased usage of these materials. The latest developments of materials with known lightweight credentials will be considered, along with new joining technologies which permit these materials to retain more of their advantages after joining. The roadblocks will be identified and a series of strategies proposed to overcome them. Specific Designs will be proposed and developed, pulling together complementary materials, manufacturing technologies and fabrication techniques which offer lightweight solutions for high volume automotive suspension applications. The focus is on bringing these advantages to the mass market.

Development Plan

The research development plan is progressed through several chronological stages:

1, Identify the need.

Consider the need for vehicle lightweighting, specifically chassis lightweighting.
Identify the benefits which would accrue from a lighter design.

2, Benchmarking

Study the current solutions to the problem. Compare technologies on currently successful vehicles. Identify the key materials, joining technologies and finishing methods.

3, Limitations

Evaluate and criticise the current solutions. Identify the limitations of technologies in current use, and why the limitations have been previously accepted by the industry.

4, Propose Solutions

Propose alternative approaches to circumvent the current limitations. Identify Material, Process and Joining technologies and look for novel and beneficial synergies. The solution should offer at least equivalent durability and strength whilst improving lightness and stiffness.

5, Joining Trials

For the materials selected as potentially feasible, conduct joining trials using the selected joining technology to confirm suitability and select the most effective route. Once the material and joining technology is decided, conduct further welding trials on different joint configurations. Following these trials, conduct mechanical testing for relevant configurations.

6, Design

In parallel with the Joining trials above, produce a design concept which embraces the selected material, joining process and surface technology to provide an integrated and functional product. Optimise the design in the virtual world and compare it to existing designs. Consider manufacturing feasibility to ensure that the proposed design is realistic.

Subsequent Activities (post-thesis)

Following a satisfactory design being proven in the virtual world and the completion of successful welding trials, a further plan of work would be proposed following this thesis to develop prototype extrusions and optimising their assembly utilising a Design of Experiments approach to optimise the welding parameters. The prototypes, assembled with bushes and ball joints, would then be strength, stiffness and durability tested on servo-hydraulic test equipment.

Discussion and Technology Selection for the Design

From the research conducted to date, Aluminium offers an attractive proposition for lightweight suspension components. In comparison with the steel arm in the benchmark study, it exhibited the highest lightweight index. However, the manufacturing technology of this solid-section arm resulted in high cost. More efficient use of the aluminium is required to reduce cost and weight still further. Pressing the part from sheet aluminium is not viable as the thick material section required to compete with steel would reduce or cancel out the intrinsic material weight saving.

Neither is tubular construction the answer. The bicycle frame study indicated that when aluminium is MIG or TIG welded, which tubes require for their fillet welds, aluminium and steel frames exhibit little difference in weight. The two primary limitations of aluminium are its reduced stiffness and strength. If material may be moved away from the neutral axis, the stiffness may be improved and the imposed loads reduced, permitting a lower yield strength material to be specified. This may be achieved by the use of extrusions, which also have the advantage of a virtually free design profile in cross-section, permitting strength to be added exactly where required.

The extruded aluminium proposal still requires an appropriate welding technology. From the welding review, any fusion technologies such as MIG and TIG are problematic, and cold processes such as self pierce rivets insufficiently robust for high peak load applications such as suspensions. The new process of friction stir welding appears to offer the optimum combination of weld attributes. As a solid state rather than a fusion process, the detrimental effects of high residual stress and distortion are greatly reduced. Fatigue initiators such as heaped irregular profile weld metal are avoided. If the welding process can be less variable, as with friction stir welding, then material thicknesses may be reduced and lightweighting may proceed in safety. The adoption of FSW for the airframe of the Eclipse business jet as researched in Section 4.3, FSW Applications in other Manufacturing Sectors, gives confidence in the process for safety critical aerospace applications.

The utilisation of friction stir welding with high strength steel was also considered, but the results of the initial trial indicated that the higher temperatures inherent in FSW of steel would be an issue. For steel, friction stir spot welding is currently a more viable option, where the intermittency of the tool contact with the component mitigates the thermal issues and the consequent tool erosion.

Unlike many welding technologies, FSW is more easily applied to aluminium than steel, and the benefits are also greater in aluminium. The next chapter will therefore develop a design concept for an aluminium suspension arm utilising extruded sections, joined by FSW.

5. Design of a FSW Aluminium Extruded Arm

From the discussions given in Chapter 4, it is concluded that a new design of arm is required which utilises aluminium for lightness. Extrusions may be specified in order to replace the strength and stiffness lost in the transfer from steel. Additionally, friction stir welding would be used as the joining technology to avoid the pitfalls of specifying MIG welding for aluminium. The next step was to produce a viable design.

In order to have a comparison with existing industry standard designs; a current steel design from a leading volume manufacturer was taken as the benchmark. The design comprise an upper and lower steel shell, internal steel stiffening plates, a solid front rubber bush, hydraulic rear bush and a ball joint. The primary forces acting on the part are illustrated in Figure 11.

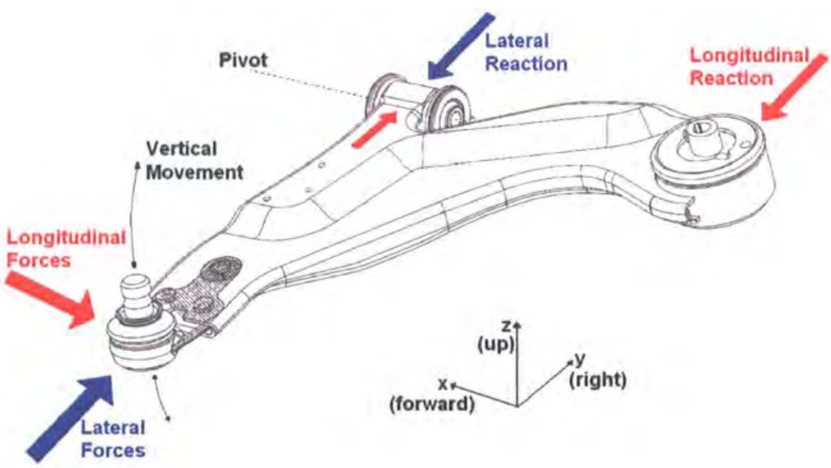


Figure 11 - Principal Loads Acting on Reference Arm

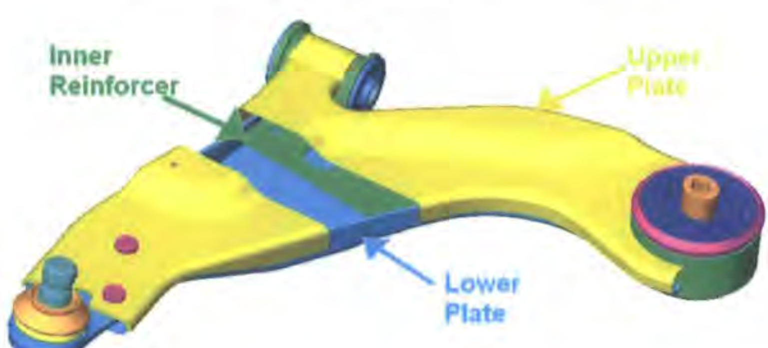


Figure 12 - Section of Reference Arm Showing Internal Stiffeners

It was also recognized that the aluminium design must also compensate for the strength of the inner reinforcement plates built into the steel reference arm as shown in Figure 12. The design concept was to utilise extruded sections of aluminium, hardened prior to welding and cut to length before being FSW welded, machined and assembled. The installed location in the vehicle may be observed in Figure 13. The design concept had to satisfy the following fundamental criteria: to have at least equivalent strength and stiffness to the steel product, to be significantly lighter, and to utilise process and construction advantages to overcome the intrinsically higher cost of aluminum.

Figure 13 - Reference Arm in Installed Position.

The design of the extrusions also had to follow certain process guidelines: to have a reasonably consistent wall section to assure full die filling, to use radii to reduce intersection stresses, to ensure welded sections are compatible with proposed FSW tooling and to consider tolerances and therefore machining requirements.

It was soon realised that an important constraint would be the size of cross-section of the extrusions. Small cross sections up to 200mm or even 300mm CCD (Circumscribing Circle Diameter) are economical to tool and productionise, as many companies can offer this service and competition holds costs down, but they will require additional assembly and welding costs. Larger extrusions are available from overseas facilities, (around 500mm to an extreme 750mm CCD) often targeted at aerospace applications. These are capable of extruding the arm in one-piece, but tooling is much more expensive and requires complex mandrel design to facilitate the forming of the voids. The limited number of companies able to do this work, the aerospace customer base and the remote location of the suppliers all adding cost. Initial tooling estimates indicated tooling costs at least double for the single piece design compared with the sum of the multi-piece design.

With the steel design, the LH and RH arms were different, even prior to assembly of the arms and bushes, necessitating two sets of pressings to be designed, tooled up and controlled. A further advantage of the extruded concept was that up to the point of machining and assembly, one fabrication could be utilized for both LH & RH arms. This halves the tooling cost and minimizes the part count, with additional savings in the 'invisible' costs of stock control and logistics.

Another issue was identified with regard to optimizing the existing steel design for aluminium extrusion. The axis of the front bush was horizontal in the steel design, this would not lend itself to an extruded design, as ideally all features need to lie in the plane of extrusion, and a vertically aligned bush would therefore be preferable. A review of the previous benchmarking exercise and further research shows that other similar designs do have vertical axis bushes, some manufacturer's noted for excellent ride and handling fit a second vertical ball joint in this location in lieu of a bush to improve wheel location. It was decided to proceed with a vertical feature which could accommodate either a vertical axis bush or a ball joint.

5.1 Initial Design

This initial developed design as seen in Figure 14 satisfies the concept, but exhibited difficulties in accommodating the desirable objective of locating the weld ends away from potentially highly-stressed areas. This is beneficial as welding; even FSW, will add stresses which are detrimental to fatigue life. To attempt to satisfy this requirement, a new design was initiated with an extruded circular centre circle, around which were arranged the three arms. The advantage of this was that the three arms could be attached with a single circular friction stir weld which was inboard and therefore away from the high stresses occurring at the perimeter of the assembly. This also reduced the number of exit holes from the FSW process from three to one. This design also had self-locating features built into the extrusions. These would assist in assembly fixturing and give a level of mechanical connection in the event of loss of weld integrity in service. This design is similar to that shown in Figure15, but with four pieces rather than five.

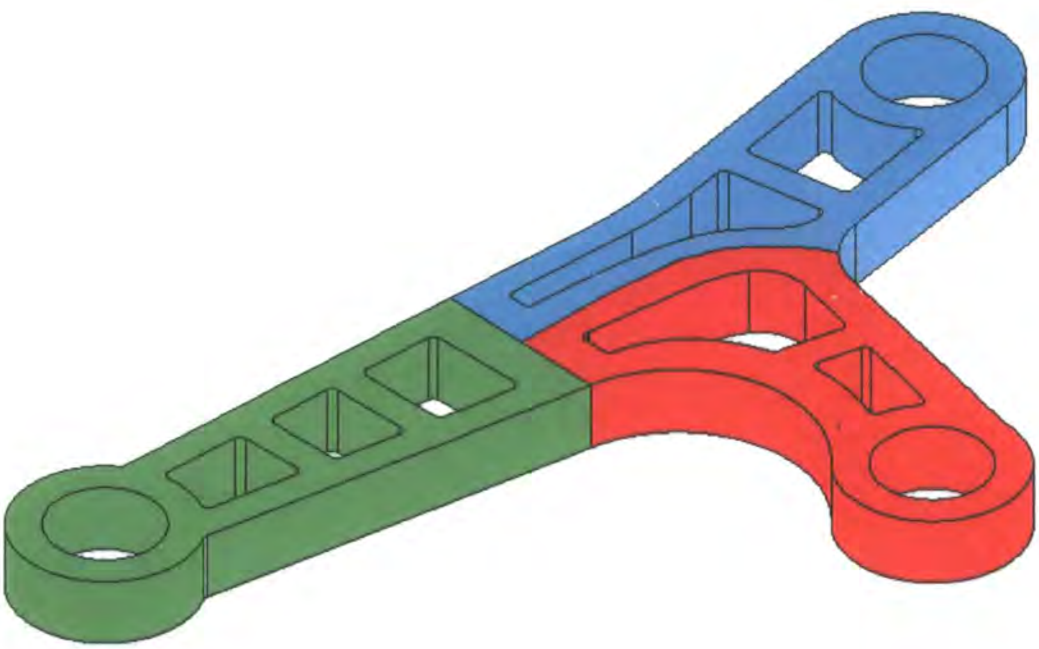


Figure 14 - Initial Design of Extruded Arm

This design enjoyed the advantage of the ball joint and front bush arms being identical cross sections, and therefore suitable to be cut from one extrusion, minimizing tooling cost, but this also resulted in the arm to the rear bush being longer than others and outside the ideal CCD limitation of 250 mm. This arm was redesigned into two pieces, with a second FSW added to join the two. The finished design being 5 pieces with only 2 friction stir welds for assembly.

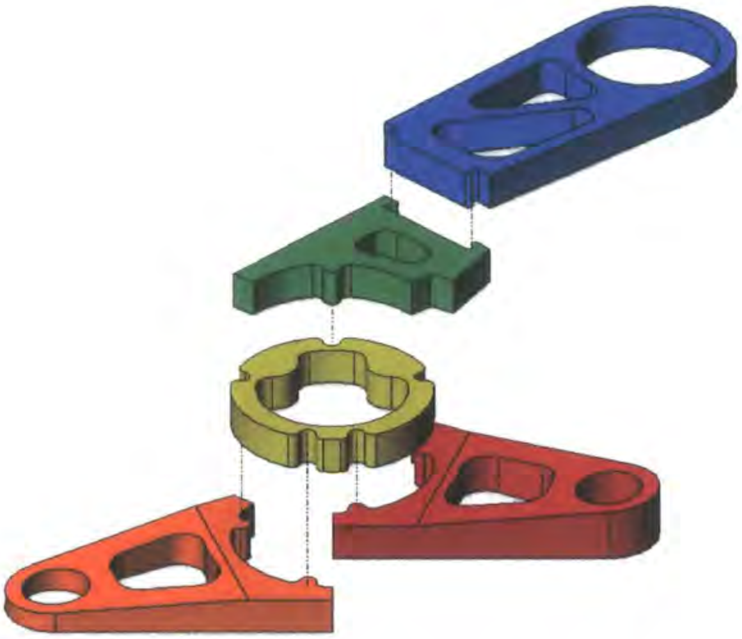


Figure 15 - Assembly View of the Five Extrusion Design

Figure 15 shows the final development of the five extrusion design. Upon evaluation, the advantages were seen as the requirement for only two welds, and only four extrusions to produce the five sections, as one is reversible. The tapered section approach was deleted on later concepts as more efficient designs were developed to accommodate the ball joint articulation requirements.

It was decided to check the load bearing capability of the design. From the many Finite Element (FE) analysis tests performed on the original steel arm, the 'forward kerb impact' test was taken as potentially the most severe design case, i.e. most likely to lead to buckling and therefore failure of the arm in service. The design was evaluated and dimensions were optimized by FE analysis as part of an Undergraduate project (44). The stress analysis results were compared to the data for the original steel part, which had previously exhibited a load limit on this test. The initial dimensions of the design were taken as the 30mm extrusion depth and 10mm general section thickness.

Discussion of the Design and Materials The extrusion depth (the sawn-off thickness) has been used as a variable to optimize the stresses in X and Y directions as imposed by the Kerb Strike event. The Z forces, i.e. wheel vertical movement, were also considered, but as these loads are transmitted straight into the suspension strut, the arm has little Z loading to absorb, only the torsional loads imposed by rotation of the arm against the rotational stiffness of the bushes, which are considered minor.

Several iterations of FE analysis were carried out, varying section thicknesses, radii and extrusion depth to result in a mass, without bushes and ball joints, of 2.3kg, saving 29.1% from the existing steel design. Stiffness increases by approximately 20%, based on an extrusion depth of 22mm, and a section thickness of 10mm (44).

A decision on material grade was required. From considerations of strength, weldability, corrosion resistance and extrudability, initially a 5 series alloy, 5050, was selected for the initial FE iterations in the unhardened condition and, to be conservative, neglecting the beneficial work-hardening effect which will accrue from the extrusion process. After further investigation the material selection was re-considered in order to improve strength. 6000 alloys were found to be generally suitable for automotive applications, 6082 was researched as an appropriate grade. In order to minimise the reduction in strength in the transfer from steel, an alloy in the harder T6 condition would be required. Investigations indicated that this would be acceptable with FSW as the joining method. Some reduction in properties in the weld were to be expected, but the design allowed for this by location the welds as far as possible away from edges and peak stresses and surrounded by unwelded material.

Manufacturing Considerations The extrusion depth also affects the welding arrangement. It is envisaged that in production, the extrusions will be welded from both sides simultaneously. This saves half the welding time and prevents distortion about the horizontal axis. With a 22mm extrusion thickness, if a full thickness weld were required, a tool of depth 11mm would be theoretically required. This would be too wide to permit optimization of the section thickness of the extrusions. The FSW tool is usually designed with the insertion diameter similar to the insertion depth, 11mm in this case. The shoulder diameter is around 3 times the insertion diameter, or 33mm. This needs to operate fully within the safe width of the material to be welded, to prevent erosion of the side flanks under the welding loads. This will require approximately 40mm of flat face, giving a minimum 20mm section width.

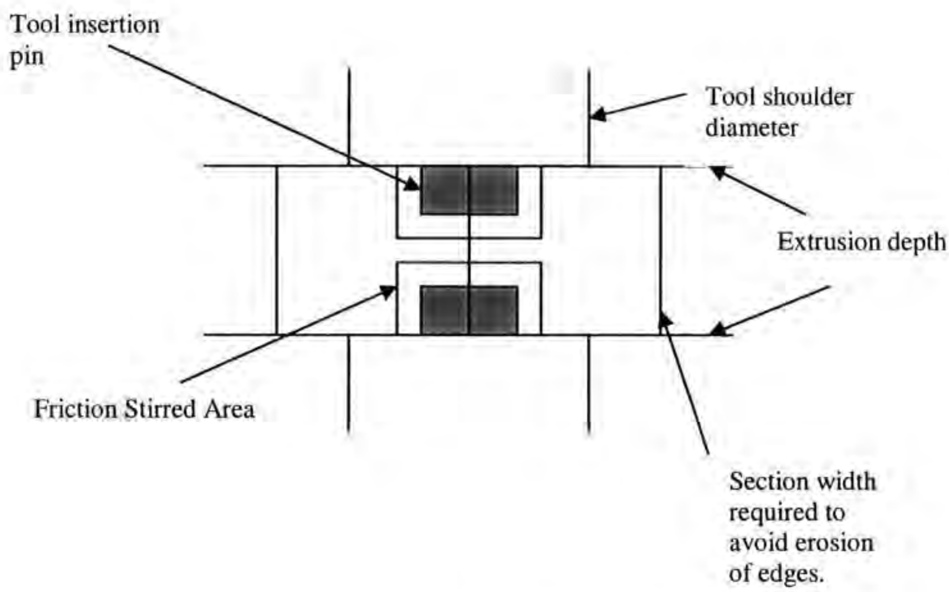


Figure 16 - Friction Stir Welding Considerations

However, FSW tends to join materials at a greater depth than the tool insertion depth, and allowance should be made for this characteristic, even though the extent will not be known until sections are taken from welded prototypes. Also, it is not yet determined how much weld depth is required to transmit the forces through the weld. If a 5mm tool insertion diameter is utilised, this may give a joining depth of 7mm per side, leaving a partially or unfused zone of 8mm at the centre, around the neutral axis where it is less critical. This may be found to be sufficient in testing. If not, provision should be made to increase to an insertion dia. of 6mm, reducing the potentially unwelded zone to 6mm. Section widths at weld points may therefore be reduced to 12mm. Figure 16 illustrates the issue.

Several design requirements must be met to adopt the extruded design to replace the steel design in the area of the ball joint, but the reward is a further reduction in the piece part count as the current rivets may be deleted. It may be observed that the original ball joint is mounted to the arm at an angle for reasons of articulation. In order to use a ball joint as designed i.e. without re-designing it with increased articulation angles, the extruded design must permit the ball joint to be mounted at the same angle as the steel design. To achieve this, the bore of the extrusion will be designed smaller than necessary to accommodate the machining, i.e. have addition thickness designed-in.

A vertical milling tool as illustrated in Figure 17 would then be introduced to the hole which would both machine the bore and spot-face the underside of the extruded arm to the correct angle. If additional clearance is required around the ball joint the top face of the extrusion may additionally be milled away in this location. The same machining facility may be used for LH & RH arms if volume requirements permit as the process is a mirror image, further reducing capital investment.

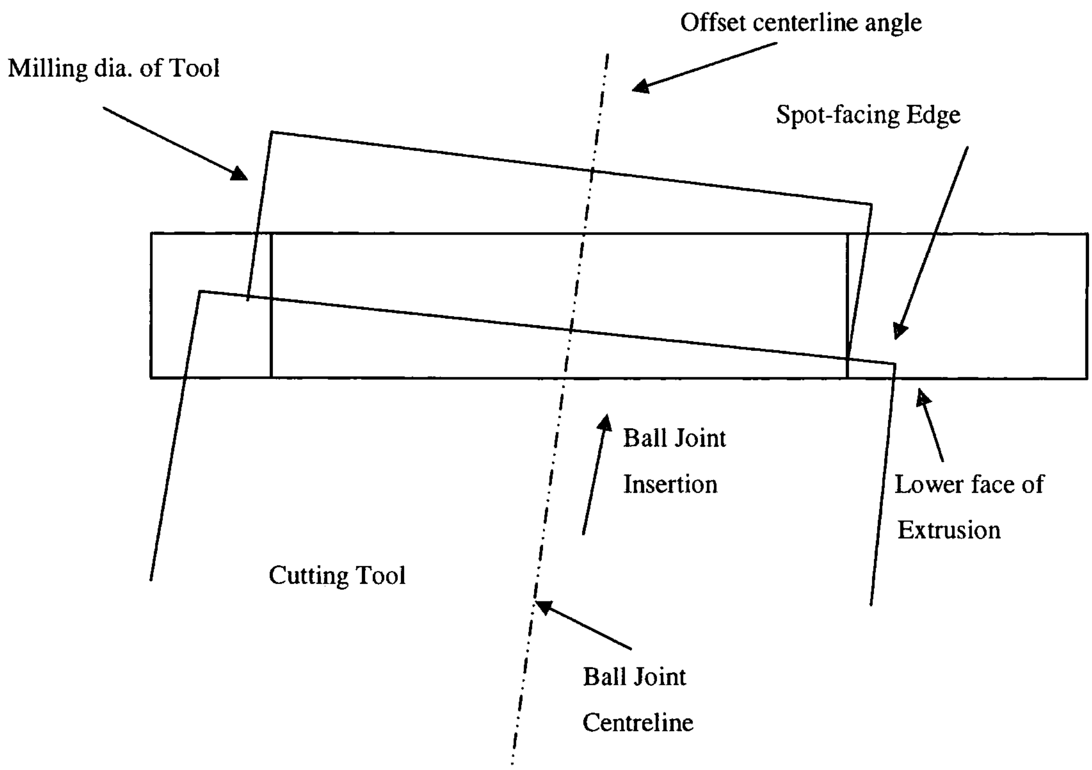


Figure 17 - Design of Ball Joint Pocket

Process Manufacturing Issues The process layout would be relatively simple compared with the steel Benchmark component, and require minimal capital cost. The process flow would be divided into supplier and subsequent in-house activities. An initial consideration of the production sequence would include the following elements:

Supplier Activities

- Extrude and harden each sectional profile.
- Cut extrusions to agreed shipping length (6m).
- Ship to site on Just-in-Time delivery schedule.

In-House activities

- Cut extrusion lengths to required width (approx. 30 mm) with 3mm high speed saw.
- Locate a set of extrusions in welding fixture.
- Apply automatic clamping & FSW from both sides simultaneously.
- Release clamping, remove arms.
- Machine parallel holes for front and rear bushes.
- Send alternate parts to ball joint machining fixture to suit RH or LH requirement, as this machines the angular rebate for the ball joint from different sides of the arm to achieve the same angular offset on differently-handed parts.
- Convey through abrasive media machine to remove welding flash and sharp edges.
- Interference assembly for Rear bush, Front Bush then Ball Joint.
- Pack to protective stillage and ship to customer.

The cost of a painting process is also saved, as aluminium of recognised grades is acceptable for chassis applications. Corrosion trials would confirm whether there would be adverse galvanic reaction between the outer steel components of the existing bushes and ball joints when in contact with the aluminium. If this is found to be a concern then the small steel parts in contact may easily be also be re-designed as aluminium for the high volume applications.

It is an important design consideration that the interference fit bushes and ball joints remain in place once they have been assembled. The interference fit will have been carefully selected to ensure that this is the case for the existing steel design. If the same interference-fit component dimensions were used for insertion into aluminium then two adjustments would be required to ensure a satisfactory retention.

Firstly, consideration must be given to increasing the amount of interference specified; this is due to the reduced strength of aluminium in comparison to steel. Secondly, the new, higher interference may overload the ring of aluminium around the inserted bush or ball joint. The hoop stress will have increased, and if a section thickness similar to steel is used then there may be insufficient area to take the load. Fortunately, the existing extrusion design exhibits considerable additional wall thickness which is relatively lightly loaded, permitting the interference to be increased safely. Testing based on a Design of Experiments approach would be completed to optimize and test the interference prior to production to confirm this.

5.2 Single Piece Arm Design

It was decided to evaluate a single piece design as shown in Figure 18 in order to consider if welding could be eliminated entirely, producing the component only from a single extrusion which would be cut to length after hardening.

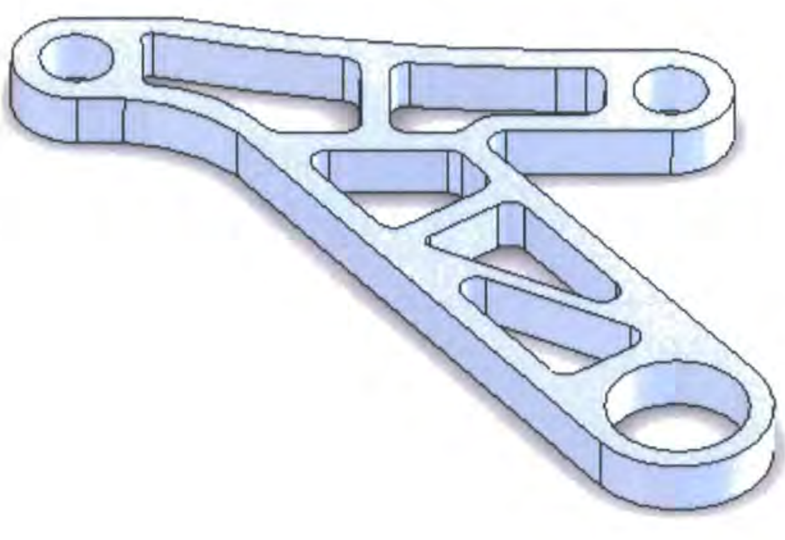


Figure 18 - Single Piece Arm Design

The initial one piece design as seen in Figure 18 follows the shape of the five piece design, as a starting point. Once drawn, it was considered that the design was too slender, and the centre of the extrusion should be increased in size to reinforce each arm and reduce the opportunity for them to fail as Euler Struts.

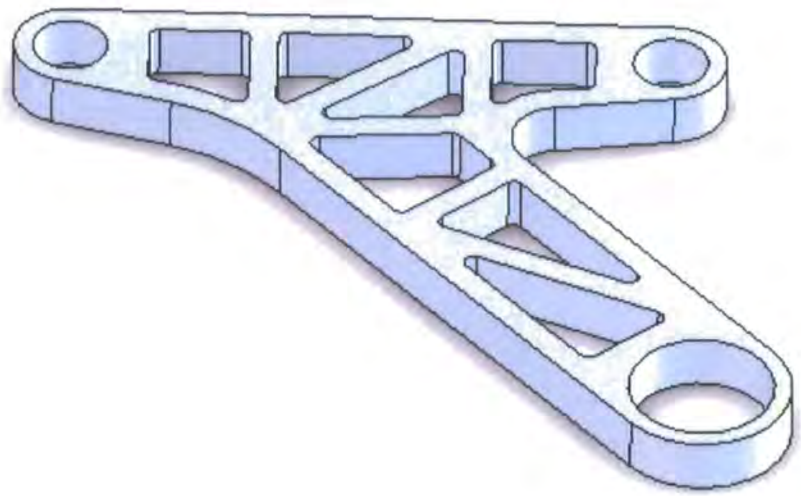


Figure 19 - Modified Single Piece Arm Design

The maximum CCD found to be available worldwide for extrusion is 750mm, but costs rise exponentially towards this figure. The initial design constraint of 550mm was increased to permit an improved cross section, see Figure 19. The modified design was therefore constrained to 600mm CCD for the component, plus 50mm for the necessary die circumferential location feature. Material cross sections were of similar thickness to minimise extrusion die float during production, for consistent dimensions.

The design was analysed by the Finite Element method as a further Undergraduate project (45). Loading conditions of 23kN were applied, giving a deflection of 10.5mm. A conservative initial extrusion depth of 40mm was selected. The results indicated that this could be reduced to 30mm with wall thicknesses of 12.5mm and fillet radii 5mm. Further analysis and optimisation reduced the walls to 10mm, and the overall weight to 2.05kg. The final design of the single piece arm is shown in Figure 20.

The original material selection of unhardened 5050A-0 material with properties 145 MPa Proof stress and 300 MPa Tensile Stress as used up to the final 5 piece design was upgraded to 6082 T6 material for the single piece and subsequent 3 piece designs, giving enhanced properties which include a Proof Stress of 310 MPa and a Tensile Stress of 340 MPa. This is approaching the limits of extrudability, but high strength is required to compete with steel designs. Friction stir welding can join T6 condition alloys satisfactorily, unlike other fusion welding methods where much of the hardening is lost during welding. A factor of safety of 1.4 was utilised on the 0.2% Proof Stress to give a maximum Design Stress of 222 MPa (45).

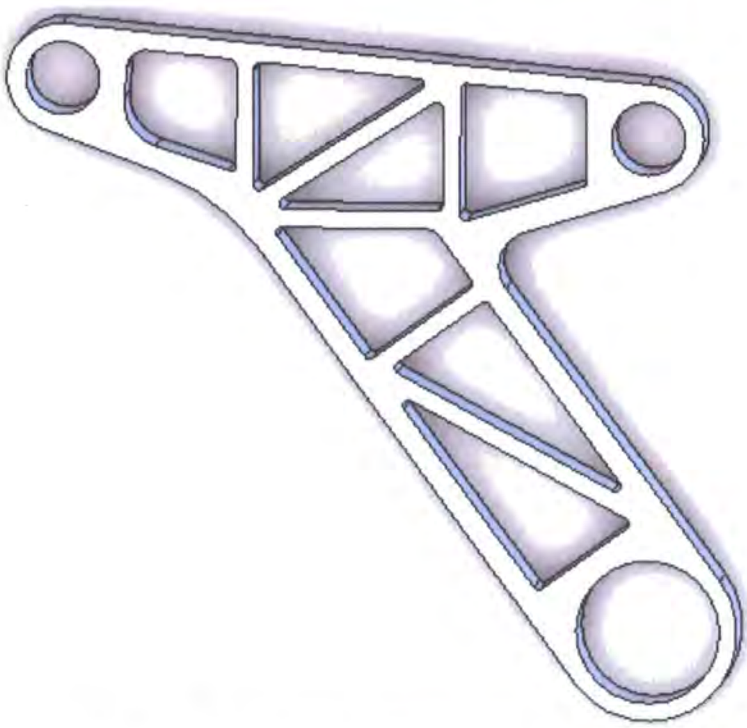


Figure 20 - Final Design of Single Piece Arm

A final analysis indicated that high stress areas had been further reduced, the majority of the arm experiencing less than 95 MPa. A further reduction in depth was considered, but there are practical issues for bush assembly and Z direction strength if the depth is excessively thin. The maximum stress is 208 MPa, with an extrusion weight of 2.08kg (31).

The five piece design and the one piece design were compared, and assessed in the light of the experience gained since the five piece design was conceived, particularly from a visit to an extrusion company. It was decided that the 5 piece design was too complex in terms of tolerance build-up and tapered sections. The one-piece design, whilst simple and effective, required large extrusion presses to produce which were generally only utilised for high cost aerospace products. This would not be economical for low-margin automotive products. Other economic factors such as extrusion wastage through wider cut-off widths and discard loss also counted heavily against the one-piece design. An optimum design was therefore required which utilised a simplified multi-piece design from economically sectioned extrusions, on the basis that fabrication costs would be outweighed by not having to fund the cost of the large scale extrusions. A three-piece design was therefore developed.

5.3 Final Three-Piece Design

The initial concept of a three-piece design is shown in Figure 21 and utilises two pieces cut from the same extrusion to save tooling cost. The weld joints are simple butt designs. This was considered to have resulted in the third leg being too large for economical extrusion, and the weld joint design insufficiently robust. To overcome the issues in the first three-piece design, the modified design in Figure 22 has a larger centre section, still within the CCD limit This has the effect of shortening the third leg, which therefore preserves an acceptable CCD. The fragility of the weld concept is strengthened by mechanical interlock features which reduces fatigue notch sensitivity.

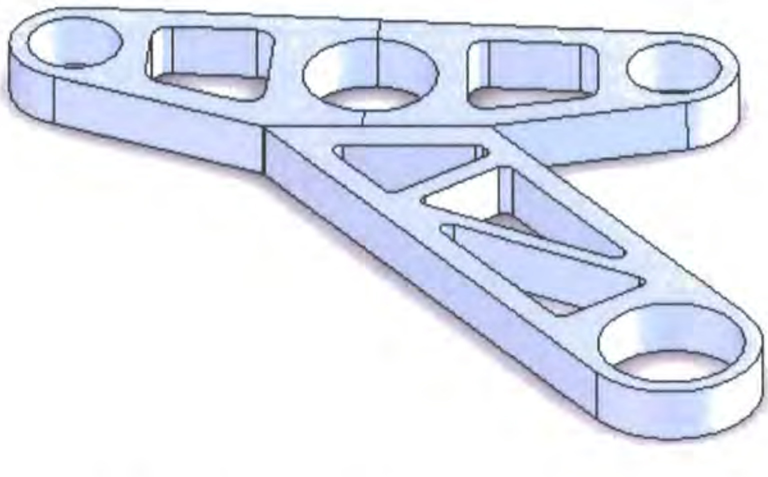


Figure 21 - Initial Concept of Three Piece Arm Design

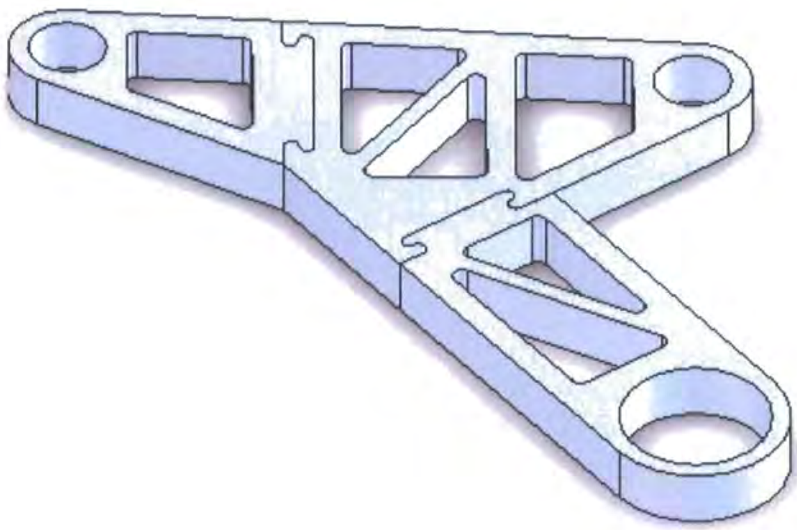


Figure 22 - Modified Three Piece Arm Design

Table 4 - Design Comparison

Design at specified extrusion thickness. All 6082 T6 Material.	Mass (g)	Reduction of Mass (%)	Stress Max. MPa	Ball Jt. Recession @26kN	Stiffness (N/mm)	Stiffness Increase (%)
Best 1 Piece @ 40mm	2935	9.8	158	4.72	4876	120
Best 1 Piece @ 30mm	2077	36.2	204	4.74	4852	119
Best 1 Piece @ 25mm	1810	44.4	247	4.79	4802	116
Best 1 Piece @ 20mm	1492	54.15	202	4.82	4772	115
First 3 Piece @ 30mm	2742	15.7	215	4.67	4928	122
Final 3 Piece @ 30mm	**2354**	**27.7**	**189**	**4.74**	**4847**	**118**

Finite Element iterations of several one-piece and three-piece designs of varying cut-off thicknesses are summarised in Table 4. These were assessed to obtain a final design which balanced the required performance criteria. One-piece designs offer the best performance package, but are not feasible from a cost and manufacturing feasibility viewpoint. The final design of three-piece arm is shown in Figure 23 which provides optimised wall thicknesses, radii and extrusion thicknesses. The minimal extrusion CCD's are easily manufacturable and FSW permits the required joining to be achieved in the most efficient manner. Compared with the steel base design, the weight of the arm is reduced by 27.7%, with an increase in stiffness of 118% whilst remaining within a maximum design stress of 190MPa (Max. allowable 222MPa) (31). Furthermore, as it would not be known exactly the extent of the weld penetration until the prototype weld trial stage, the welds were engineered to be in low stress areas where partial penetration welds would have the required integrity.

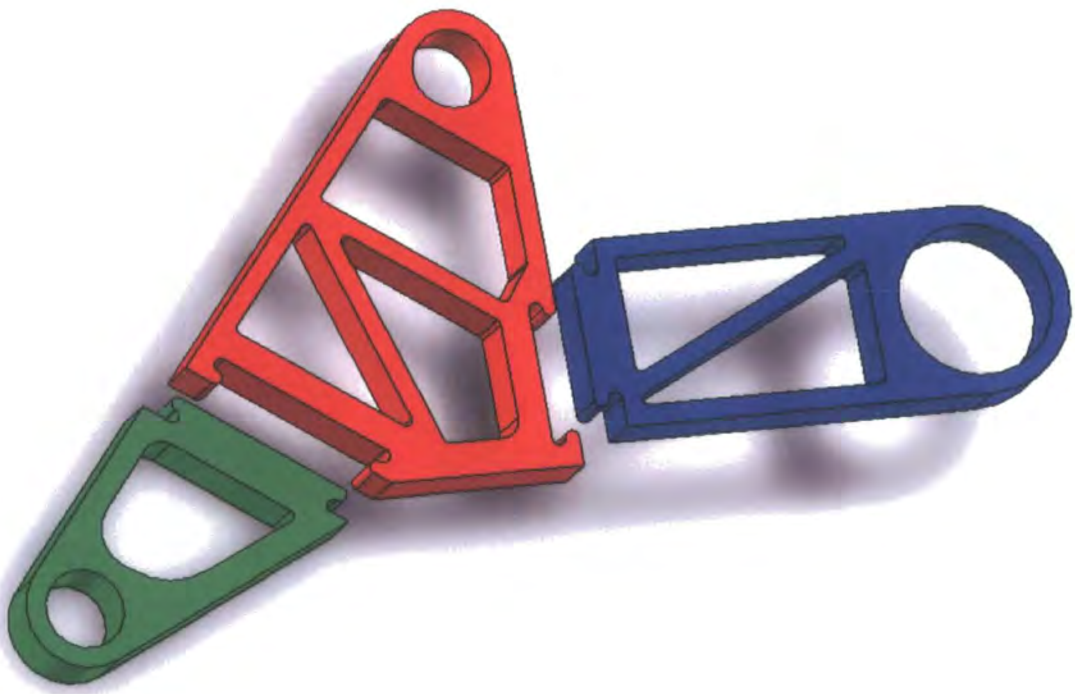


Figure 23 - Final Design of Three Piece Arm

6 Experimental FSW Trial of Proposed Welding Geometries

It was decided to initially investigate the feasibility of Friction Stir welding of Steel compared to Aluminium, as most suspension systems are currently steel. The principal relevant difference is the melting points of the two materials. To weld aluminium, a tool-steel tool has a melting point sufficiently higher than the aluminium, such that the aluminium becomes plastic before the temperature is raised to a level which detrimentally affects the steel tool. To weld steel, a tool material is required with a melting point higher by the same order over the steel material to be welded, whilst also retaining mechanical strength and abrasion resistance. Currently, tool materials capable of economically satisfying all the above requirements for steel FSW are not available. Steel may currently be friction stir welded, but with limited tool life.

6.1 Initial Trial: Friction Stir Welded Steel

Despite the tooling durability limitations, considerable interest is being shown in steel applications, and it was decided to quickly determine the current position on linear steel FSW prior to developing a main trial on FSW of aluminium. This would be progressed by FSW welding steel plates and conducting basic metallurgical tests. Plate materials of medium strength in thicknesses typical of chassis construction were supplied to TWI where they were produced as butt welded samples to evaluate the feasibility. Four samples were produced, samples 1 and 2 were XF350 material: samples 3 and 4 were XF450. This was not a rigorous trial, but an initial evaluation to assess the current state of steel FSW against the more advanced Aluminium FSW position. The basic trial was performed on a converted vertical milling machine fitted with a FSW tool.

Two lengths of steel plate were butted together and clamped to permit a 300mm long weld to be performed. Considerably more heat was being generated than with aluminium samples, with the tool temperature running at red heat after approximately 100mm, and increasing further with weld length. The tool appeared undamaged following the short trial. This was repeated with a higher grade steel material. Following the trial, the plates were cut into trial coupons for cross-joint tensile tests to determine the effectiveness of the welding process.

Figure 24 – Steel FSW Tensile Test Specimens

Table 5 - Results of Exploratory FSW Trial for Steel

Sample	1	2	3	4
Width (mm)	12.92	12.98	12.77	12.78
Thickness (mm)	3.9	3.84	3.55	3.87
Cross sect (sqmm)	50.39	49.84	45.33	49.46
Gauge length (mm)	50	50	50	50
Yield load (kN)	-	-	22.0	23.0
Yield stress (MPa)	-	-	485.3	465.02
Tensile load (kN)	26.8	25.8	25.2	26.1
Tensile stress (MPa)	531.9	517.7	555.9	527.7
% Elongation (%)	10	11	11	12
Fracture Location	weld	weld	weld	weld

The tensile test samples are shown in Figure 24, and Table 5 gives the results of the initial steel FSW trial. All four welds exhibited similar results, indicating a consistent process. All parts failed at the joint, which is to be expected on a partial penetration weld, but the failure loads were acceptable. It was noted that the welds were not full material thickness; therefore the true failure stress will be slightly higher. Subsequent trials would utilise a longer pin for increased penetration, but at the risk of inadvertently attaching the welded material to the backing bar. The yield loads were estimated, where possible by observing the drop in load increase. It is an estimation and would tend to be optimistic.

It was noted that despite the high temperatures observed during the welding, the bowing of the plate once it had cooled was considerably less than that which would be expected from a MIG welded sample. This was expected to be due to the absence of a weld bead outside the plane of the plate, where the residual tensile stresses imposed would have a greater effect on distortion.

Development is taking place to develop improved FSW tooling for steel, but due to the current limitations over tool cost and durability, this research has moved on to other materials, but in the expectation that suitable economic steel FSW tooling will become available. Following this informal trial, it was felt that the current limitations of linear FSW for steel had been adequately exposed, in line with the expected limitations, and that the main trial would be performed on aluminium components.

6.2 Friction Stir Welding Trials of Aluminium

This section covers the methodology for the Feasibility Trial of Friction Stir Welding for Complex Automotive Suspension Assemblies. From research, it had been decided that aluminium, principally in extruded form, and subsequently fabricated by friction stir welding, would be an optimum route for lightweight automotive suspension assemblies. This should now be tested in practice; however due to the lack of experience of programming a friction stir welding machine, or of any operational limitations inherent in the process, this experience had to be gained if an FSW approach were to be feasible. It was therefore imperative to obtain access to a friction stir welding machine in order to conduct practical trials on the type of materials and joint details proposed.

FSW Machine Selection Requirements for, and selection of, the FSW machine needed to be determined. Upon examination, development of FSW machines has diverged down two paths: Rigid Bed and Robotic machines.

Rigid bed machines usually have 3 primary axes plus head articulation, and are not dissimilar to a vertical CNC milling machine in concept. They are ideally suited to 2D FSW welding, and the machine rigidity easily provides the support for the tool. A production machine may be relatively unsophisticated with regard to controls, once optimum operational parameters have been determined. However, for a development machine it is necessary to observe and adjust the operating parameters in order to optimise the process to achieve the necessary weld quality at the optimum travel velocity, therefore a machine with greater control of variables was required.

For Robotic FSW, the rotating tool and the associated drive are mounted on an industrial robot. The robot articulation is much superior to the rigid bed machines, with 3D welding being possible. The robot however is considerably less stiff than the rigid bed machines, and heavy duty robots must be specified, along with sophisticated feedback controls to give stability under tool vibration conditions if fast process speeds are to be achieved. These issues are being addressed with TRICEPTS type robots which utilise three hydraulic rams in unison. With this type, articulation is reduced, but rigidity is much improved. For this application 3D functionality is not required, so the rigidity issues implicit in robotic machines may be avoided.

The construction principle of extrusions cut to length is intended to provide a weld path which may be constrained to 2D. This will minimise investment and simplify operational parameters. Machine rigidity is important to sustain high production speeds. From the previous observations, a rigid bed machine was required, complete with controls and feedback to enable it to function as a development machine. Access was required to a latest generation machine in order to exploit the recent developments in feedback technology.

Manufacturers of Rigid Bed FSW machines were approached and it was determined that a POWERSTIR 215T machine had been recently supplied by the Non-

Conventional Machine Tool Division of the SMART technology Group. The machine was supplied to ONERA Office National d'Etudes et de Recherches Aerospatiales and was installed at the Centre de Palaiseau, Chemin de la Huniere, Palaiseau in the outskirts of Paris. ONERA were able to offer limited access to the machine for our trials, and a development plan was drawn up to maximise the available window. The machine parameters as shown in Table 6 were advised and considered during the trial planning. The machine parameters selected for monitoring were as shown in Table 7 and the machine utilised is shown in Figure 25.

Table 6 - FSW Machine Parameters

Maximum Component Height	100mm
X axis traverse	1250mm
Y axis traverse	800mm
Z axis traverse	150mm
X, Y and Z axes at welding rate	1m/min max.
at no-load positional rate	10m/min max.
X,Y,Z Axes	30kN of thrust per Axis
Servo amplifiers, servo motors and leadscrews	Pulse encoder feedback
Ram swivel for lead leanback	+/- 5°
Max. spindle rotational velocity	2000rpm
M/C Mass	15T
Power Supply	400V, 50Hz, 3 Phase

Figure 25 - Friction Stir welding Machine used for Trials

Table 7 - Machine Monitoring Parameters

X load cell	This is the force on the leadscrew driving the workpiece along the direction of welding. For straight welds this is sufficient. For curved welds the y axis, transverse to the weld path, would also be monitored.
Z load cell	This is the vertical force on the tool driving spindle. It will always be zero to compressive.
Spindle Load	This is the load required to rotate the tool. Changes may indicate viscosity variation in the weld or a lack of penetration.
Spindle Speed	The speed of rotation of the spindle in RPM.
X Position	The location of the tool centreline along the weld.
Z Position	The tool height relative to the surface of the work, Clarified as the depth below the pre-weld auto touch condition as sensed by the load cell.
Delay	The time delay associated with tool insertion

Required Outputs The following requirements were considered as the outputs required from the exercise: To assimilate the machine setup, control and feedback systems to operate the machine, then to experiment with Aluminium sheet-to-sheet material welding by welding Aluminium Sheet to Aluminium Extrusions in various combinations and to quantify weld distortion over longer lengths. Also to monitor tool wear over the trial period, develop a judgement for clamping restraint requirements and gain an initial appreciation of factors important to optimisation of the process. 6XXX aluminium materials were selected as having suitable properties for suspension applications generally, and 6082 in the T6 condition had been the final selection for the Arm design. Therefore 6082 T6 should feature in any welding trials undertaken, along with some softer materials which may be utilised for low load attachment brackets, but still requiring to be welded to the arm.

Table 8 - Trial Weld Geometries

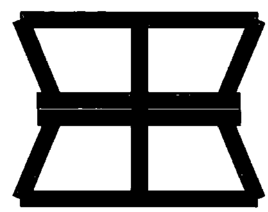
TRIAL 1 Butt Weld 2mm sheet to 2mm Sheet 	TRIAL 2 Extrusion Centreline Trial 
TRIAL 3 Butt Weld of Extrusion to 3mm Sheet 	TRIAL 4 Butt Weld of Extrusion to Extrusion 
TRIAL 5 Combined Butt/Lap Weld of 3mm Sheet over 2 X 6mm Sheet 	

Table 9 - Materials for Trial

2mm nom. (1.86mm actual) x 500mm x 55mm Grade HS30 (6082 T651)
3mm nom (2.95mm actual) x 500mm x 55mm Grade 1050A H14
6mm nom (6.31 actual) x 500 x 55mm Grade 6082 T651
Extrusion lengths were sourced: Trapezoidal section tube, Grade 6005a T6

The five trials, with weld joint details as shown in Table 8 and materials as shown in Table 9, would generate three types of recorded data:

A, The Parameter Settings, -how the machine was programmed,
B, The Limits -the extreme permitted parameters,
C, The Actual Data, as recorded by the Data Acquisition system.

Only the primary data required to understand the results is summarised in the report, including: Primary Machine Parameters, Photographs, Welding Results and Graphical representations of recorded parameters. The Set Parameters were as shown in Table 10, and the Machine Limits were set as shown in Table 11.

Table 10 - Machine Set Parameters for Trial

Z plunge depth, mm	The tool plunge depth.
Plunge Feedrate mm/min	The speed of z axis progression into the work.
Plunge Spindle Speed RPM	The spindle speed during plunge only.
Plunge Dwell	The dwell time after plunging.
Weld X position	Spindle posn. along the X axis at weld initiation.
Spindle Speed RPM	The spindle speed during welding.
Exit Z position	Height of tool retraction at end of weld.

Table 11 - Machine Limits

Plunge Force kN	Limit on max force to protect spindle
Plunge Max Force %	Limit to protect work as variation would not normally exceed this percentage.
Weld Force kN	Limit to protect tool
Max Weld Force %	Limit to protect work as variation would not normally exceed this percentage.
Security Position Vertical mm	Prevents excessive tool travel. Shoulder should not travel significantly below the surface.

6.3 TRIAL 1 Sheet to Sheet

The intention of the first trial was to prove-out FSW from first principles by utilising a simply manufactured tool rather than a purchased item. The tool design had to provide the following features:

- To fit the standard chuck feature
- To generate frictional heating in the aluminium
- To provide upward swirl in the aluminium
- To provide depth adjustment to cater for thickness variation and wear
- Not to become plastic or molten.

Figure 26 - Screw Type FSW Tool and Holder

The concept of the tool as shown in Figure 26 was to utilise a turned mild steel shank with a screw form insert. The mild steel shank was turned to 20mm diameter and internally bored clearance for the screw head from the top, and clearance for the screw shank from the bottom. The base of the shank was tapped internally to suit the screw.

The shank was tapered in to the diameter selected as the optimum shoulder width. Most of the heat input comes from shoulder friction, (typically 80% from shoulder, and 20% from tip; or screw in this case). The diameter principally controls the temperature achieved. The shoulder itself was radiused slightly (dished) to allow the plasticised aluminium to rise within it.

The screw form was provided by a standard M4 H13 Allen screw. By convention FSW threads are LH, but in the cause of easy to source materials a standard RH screw was utilised, and the spindle rotation was reversed. Reversing the spindle is not an issue for straight welds, but for curved welds the rotation can be critical relative to the direction of bend; the rotation direction is significant if the material varies in grade or thickness about the weld direction. The purpose of the screw thread is to drive the material down adjacent to the thread, and to mix it before it rises to the shoulder. The screw thread would be too fine in its standard form to allow aluminium to flow downwards around the circumference as required, therefore three additional flutes were ground around the circumference with a small grinding disc in the same direction of the thread.

The tooling setup was completed by inserting the screw into the shank with washers under the head to set the protruded length to 1.8mm (90% of nominal material thickness). The active screw was then locked in place with a long grub screw. The tool assembly was then assembled to the spindle and the rotation direction set as opposite to standard due to the reverse thread direction.

The aluminium surface may beneficially be cleaned with Acetone prior to welding, but this was not considered desirable for production and for realism the prototypes were also therefore welded in the as-received condition.

A clamping arrangement was established as shown in Figure 27 where, prior to welding, the plates were both pushed together horizontally and clamped vertically by adjustment screws. Clamping can be problematic with FSW as the heat generated during welding will expand the plates laterally and, as they cannot move laterally or vertically downwards, may rise. With thin plates, an additional option to assist location is to run a roller directly in front of the spindle to further ensure that the workpiece does not rise. The arrangement was not required in this case.

Figure 27 - Clamping Arrangement for Trial 1

Parameter Settings.

TILT

The fourth axis on this machine permits a tilt angle to be introduced.

The tilt permits the tool to be tipped backwards during forward feed, which may assist in the stabilisation of the weld condition. Ideally it should not be utilised, as it can only be set in one travel direction and therefore complicates welding in directions other than the optimised direction. It was decided to use the tilt control for optimisation in our trials, to evaluate its effects and eliminate it if possible. A small tilt angle was set for the first run; this setting is not monitored manually as it is not included in the machine performance readouts.

SPEED AND FEED

Generic advice was sought for the initial settings for both these fundamental values. These parameters are the obvious variables in the process and it was important to understand the effect of each by variation. The theory indicates that faster spindle speeds and slower travel speeds should produce more heat. In production it would be desirable to seek to increase the feed as far as possible to increase output, therefore rotational speed would be set to support the predominant feed rate, not vice versa. The X feed rate is set as X mm per rev, not mm/min as advised in the machine printout. The effect of this is to couple the feed rate to the spindle speed. The travel speed was set conservatively for the first run, to protect the tool against breakage.

PLUNGE DELAY

The tool is plunged into the workpiece to initiate the weld. It takes a short time for the shoulder to heat the work sufficiently to permit the screw to traverse. This time delay is a function of the material properties, material thickness and the shoulder diameter. It was initially set at 1 second.

ACCELERATION TO FULL FEED VELOCITY

For some materials it is necessary to accelerate the feed gradually until full velocity is reached, to allow the heat to build and prevent tool breakage. This was not considered necessary for the materials and thicknesses being welded in this exercise, and full feed was introduced immediately after the plunge delay.

VERTICAL FORCE CONTROL

On a FSW development machine such as this, the vertical force may be controlled in two ways:

(1) DISPLACEMENT CONTROL The tool would be lowered into the work until the shoulder contacts the top surface and friction heating begins. Traversing then is initiated with the tool height being fixed for the length of the weld.

(2) FORCE CONTROL A load cell on the spindle may be utilised to maintain a set force which nominally maintains the load required to retain the shoulder in contact.

It was decided to run under displacement control for the first weld whilst monitoring load, then to run on the mean load as determined by the first run whilst monitoring displacement to ensure the weld was controlled within reasonable vertical bounds.

Results A visual weld inspection rating out of 10, with 10 being optimum, was assessed as each weld was produced, and recorded for each run. Each welding process result is assessed against every parameter change and chronicled in Appendix 1. An image of the best rated result and the primary settings which produced it are shown in Table 12.

Table 12 - Trial 1 Development and Optimum Result

Z Disp. Or Load Control	Load	
Plunge Spindle Speed	1100 rpm	
Plunge Entry Dwell	0 Seconds	
Weld 1 Position	50mm	
Weld 1 Feedrate	0.5mm/rev	
Spindle Speed	1100rpm	
Spindle Direction	Std	
4th Axis tilt	1.5 Deg	
Tool Specification	Professional	

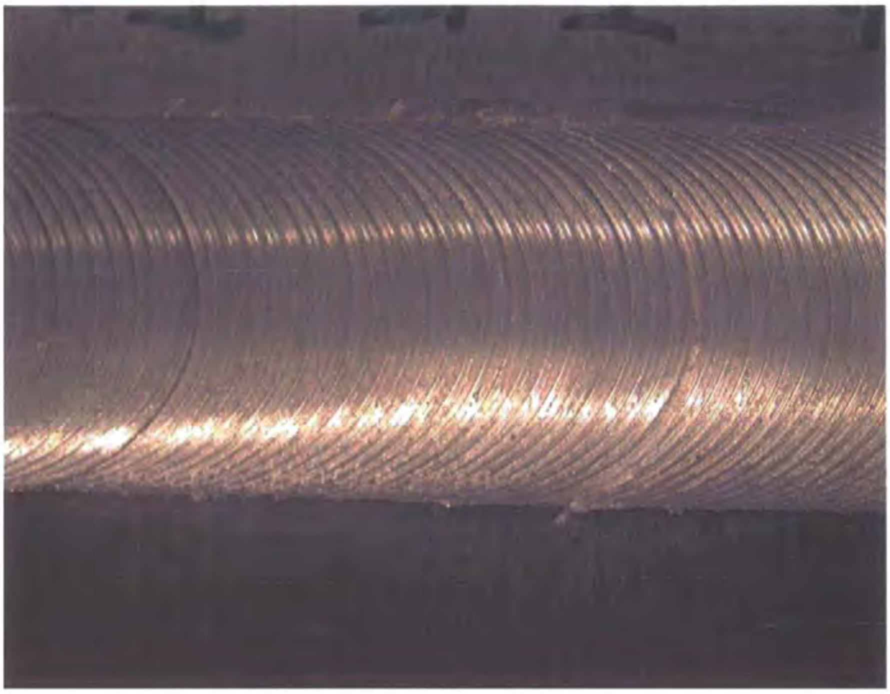


Figure 28 - Optimised Trial 1 Weld

OPTIMUM SETTINGS FOR TRIAL 1 The weld resulting in utilisation of the optimum experimentally derived settings is shown, with flash removed, in Figure 28. The important parameters were found to be a Spindle Speed of 1100 rpm, a Feed of 0.5mm/rev, a 4^{th} Axis tilt of 1.5° and a professional 2.5mm tool with coarse flutes which were more resistant to blockage, and permitted better plastic material flow around the tool. The spindle direction was reset to standard to suit the direction required for the professional tool.

The settings which were utilised for each run are recorded in Table 13, and an example of the machine readouts which were generated for each run is shown in Figure 29.

Table 13 - Optimised Trial 1 Parameters

TRIAL 1 -SUMMARY OF INPUT PARAMETERS
Source -Machine Programmed Data
Settings remain as previous unless identified as changed.

		RUN 1	RUN 2	RUN 3	RUN 4	RUN 5	RUN 6	RUN 7	RUN 8	RUN 9	RUN 10	RUN 11	RUN 12
PROGRAMMED													
Z plunge	mm	-1.8											
Z Plunge feedrate	mm/min	50											
Z Disp or Load		Disp							Load				
Plunge spindle speed	rpm	1100					1300		1100				
plunge entry dwell	sec	1		0									
weld 1 position	mm	50						40	50				
Weld 1 feedrate	mm/rev	0.1	0.5	1	0.4	1		0.5					
weld 1 spindle speed	rpm	1100					1300		1100				
Exit Z posn	mm	50											
SET PARAMETERS													
Spindle Direction		Reverse											std
4th axis backward tilt		0.25 Deg									1.5 Deg		
TOOLS													
Screw Type Used		X											
Screw Type New										X			
Screw Type Cleaned												X	
Professional													X

EXCEL TRIAL1 SUMMARY.xls

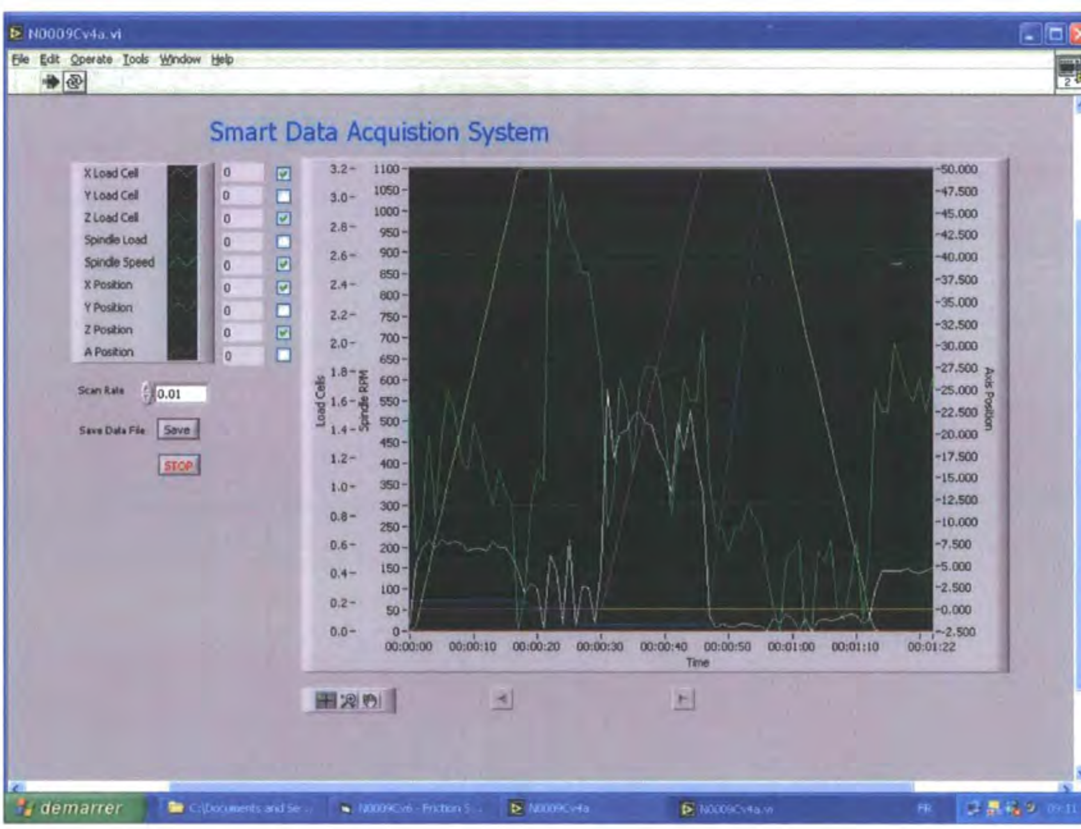


Figure 29 - Machine Monitoring Output

6.4 TRIAL 2 Extrusion Only

TRIAL 2 was carried out on extruded material. In order to investigate the potential of FSW for automotive applications, the challenges of welding extrusions must be addressed. With TRIAL 1, on flat plates, there was no problem to oppose the welding forces. With extrusions, welding forces will tend to collapse the hollow section. Some judgement is required to determine what minimum cross sections are required to resist these loads whilst still generating sufficient heat at the weld.

The purpose of TRIAL 2 was not to weld, but to evaluate the effect of welding heat on the extruded section. A single section of trapezoidal extrusion was used. By deleting a second component to be welded, the effect of FSW on the extrusion would be free of noise caused by excessive variables. The extrusion was designed with a central supporting web. By locating the FSW tool in different lateral positions with respect to the web whilst making an autogenous friction stir 'weld' the feasibility of welding to extrusions could be determined. The setup, with the tool running along the central web may be seen in Figure 30.

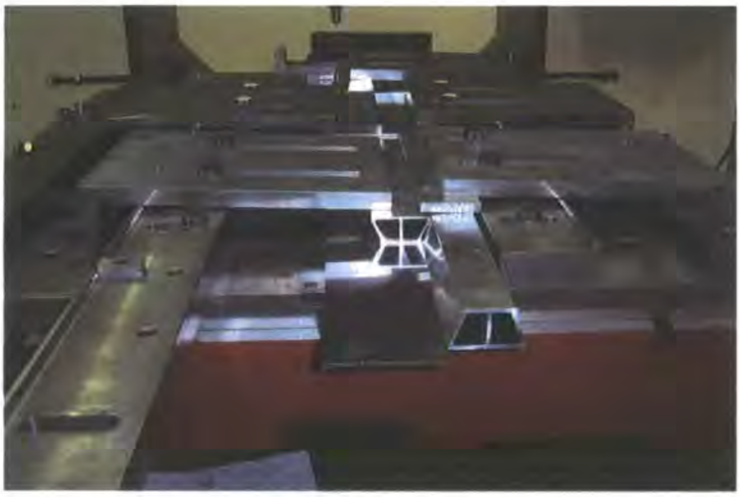


Figure 30 - Trial 2 Support from Extruded Web

The TRIAL 2 began with the optimum settings as determined by TRIAL 1, this was a reasonable assumption as the plate and extrusion materials were very similar, the effects on material grade were not known. The thermal impedance, or heat escape resistance, of an extrusion would usually be greater than a sheet material in contact with a backing plate, requiring additional heat input. However in this case it was considered that the web would act as a third conduit, assisting the thermal dispersion. The weld sequence therefore follows from TRIAL 1. The full results are contained in Appendix 2. Table 14 shows the primary settings and an image of the optimum result, which was RUN 21 rated at 8/10.

Table 14 – Trial 2 Development and Optimum Result

Plunge Spindle Speed	1300 rpm	
Weld 1 Feedrate	0.4 mm/rev	
Weld 1 Spindle Speed	1300 rpm	
4^{th} axis backward tilt	1.5 Deg	
Weld Force	2 kN	
Security Position	-2.2 mm	

Table 15 - Optimised Trial 2 Parameters

TRIAL 2 -SUMMARY OF INPUT PARAMETERS
Source -Machine Programmed Data
Settings remain as previous unless identified as changed.

		RUN 13	RUN 14	RUN 15	RUN 16	RUN 17	RUN18	RUN 19	RUN 20	RUN 21
PROGRAMMED										
Z plunge	mm	-1.8		-1.9		-1.8				
Z Plunge feedrate	mm/min	50								
Z Disp or Load		Disp								
Plunge spindle speed	rpm	1100	1300							
plunge entry dwell	sec	1								
weld 1 position	mm	50								
Weld 1 feedrate	mm/rev	0.5	0.2							0.4
weld 1 spindle speed	rpm	1100	1300							
Exit Z posn	mm	50								
SET PARAMETERS										
Spindle Direction		Std								
4th axis backward tilt		1.5 Deg								
TOOLS										
Professional		X								
SECURITY POSN'S										
Weld Force kN		6			3	1.6				2
Security Posn mm		-2			-2.4	-2				-2.2

EXCEL TRIAL 2 SUMMARY.xls

Table 15 records the input parameters for TRIAL 2. The trial illustrated the importance of ensuring that the vertical weld forces are able to be reacted by the workpiece. This extrusion had only a thin reinforcing weld, and the even with the weld path optimised to the centre, the undercut level of the best visual weld indicated that some compressive collapse of the web was in evidence.

6.5 TRIAL 3 Extrusion to Sheet

Trial 3 aimed to utilise the experience of sheet/sheet and unwelded extrusion TRIALS 1 and 2 and attempt to FSW sheet to extrusion. This type of joint will be fundamental to automotive suspension applications. The initial concern was with regard to clamping, and several attempts were made to retain the material in a flat and level manner. This would be less of a concern for productionised welding with dedicated clamping designs. The setup arrangement to butt weld sheet to extrusion is illustrated in Figure 31. For the first 'sheet to extrusion' run, parameters were reset to suit the new requirements. The full TRIAL 3 results are located in Appendix 3. An image of the optimum result and it's associated parameters for first part of the development sequence are listed in Table 16. The optimum was Run 26 rated at 9/10.

Figure 31 - Arrangement for TRIAL 3

Table 16 - Trial 3 Development and Optimum Result from Runs 22 to 26

Z Plunge	-2.45mm	
Z Disp or Load	Disp	
Spindle Speed	1300 rpm	
Security Weld Force	2.6kN	
Security Weld Position	-2.9mm	

Having achieved a satisfactory visual weld condition, it was necessary to check the material flow. An additional weld was made at the same settings and sectioned in order to determine the material distribution between the sheet and the extrusion.

As the extrusion has two heat sink routes compared with one in the sheet, it is likely that the sheet is absorbing more of the induced heat than the extrusion, giving rise to inhomogeneous mixing. The sectioning indicated that a further improvement may be made if the weldpath were moved from the centreline 0.5mm towards the extrusion. This will be tried later as a final optimisation of TRIAL 3. The optimum parameters and associated image for the second part of the development sequence is shown in Table 17. the optimum was RUN 37, rated at 9/10.

Table 17 - Trial 3 Development and Optimum Result from Runs 27 to 37

Z Plunge	-2.45mm	
Z Disp or Load	Disp	
Spindle Speed	1200 rpm	
Weld 1 Feedrate	0.3/0.5mm/rev	
Security Weld Position	-2.9mm	

At this point the Traverse Direction was changed. Previously, the accelerating side of the tool was in the sheet. Now, by reversing the Traverse Direction, the accelerating side of the tool is in the extrusion. This will have the effect of increasing temperature in the extrusion with respect to the sheet, which will offset the additional heat path out of the extrusion and give a balanced weld. As this effect is similar to moving the travel path away from the centreline, to avoid confusing the results the offset was reduced to zero with the tool running along the centreline for Run 37.

The change in feed speed was also found to be an issue as the machine was insufficiently sophisticated as to permit a seamless transition between the two; hence a step change was visible in the completed weld. The result was an improved weld on the initial 0.3mm/rev length, so increase to 0.5mm/rev was not beneficial. The optimum settings and associated image for the third part of the development process is shown in Table 18. The optimum was Run 41, rated 10/10.

Table 18 - Trial 3 Development and Optimum Result from Runs 38 to 41

Z Plunge	-2.45mm	
Z Disp or Load	Disp	
Spindle Speed	1200 rpm	
Weld 1 Feedrate	0.3 mm/rev	
Weld Lateral position	0.75mm towards extrusion	

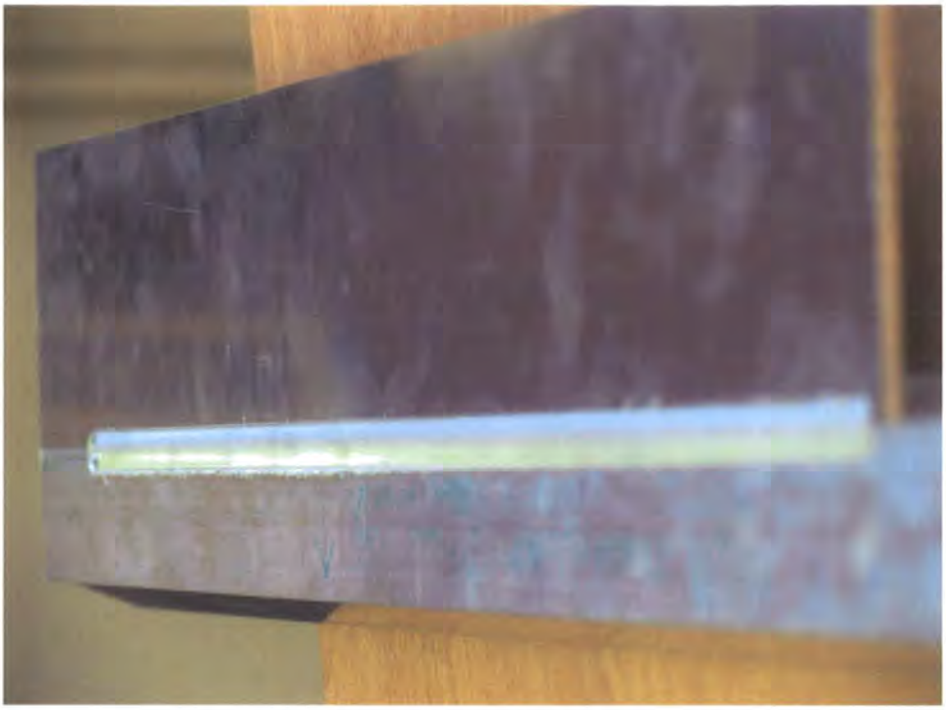


Figure 32 - Long Weld Produced Following TRIAL 3

Figure 32 shows the long weld produced with the optimum settings from TRIAL 3 to ensure that no reduction in weld quality was experienced over a weld sequence of longer duration. The parameters for TRIAL 3 are shown in Tables 19 and 20.

Table 19 - Optimised TRIAL 3 Parameters Runs 22 to 31

TRIAL 3 -SUMMARY OF INPUT PARAMETERS Sheet 1
Source -Machine Programmed Data
Settings remain as previous unless identified as changed.

		RUN 22	RUN 23	RUN 24	RUN 25	RUN 26	RUN 27	RUN 28	RUN 29	RUN 30	RUN 31
PROGRAMMED											
Z plunge	mm	-2.6	-2.7	-2.6	-2.5	-2.4	-2.45				
Z Plunge feedrate	mm/min	50									
Z Disp or Load		Load		Disp				Load			Disp
Plunge spindle speed	rpm	1300									
plunge entry dwell	sec	1									
Weld 1 feedrate	mm/rev	0.4									
weld 1 spindle speed	rpm	1300									
SET PARAMETERS											
Spindle Direction	std										
4th axis backward tilt a	1.5	Deg									
TOOLS											
Professional											
SECURITY POSN'S											
Plunge Force	kN	6									
Plunge max. force	%	10									
Plunge security Posn	mm	0									
Weld Force	kN	2.5	2.6							10	2.6
Weld max force	%	10	20	10							
Weld security posn	mm	-2.9							-3.5	-3	-2.9
WELD LAT POSN	mm	On c/l									
WELD SHORT/LONG	mm	Short									

EXCEL TRIAL 3sht1 SUMMARY.xls

Table 20 - Optimised TRIAL 3 Parameters Runs 32 to 41

TRIAL 3 -SUMMARY OF INPUT PARAMETERS Sheet 2
Source -Machine Programmed Data
Settings remain as previous unless identified as changed.

		RUN 32	RUN 33	RUN 34	RUN 35	RUN 36	RUN 37	RUN 38	RUN 39	RUN 40	RUN 41
PROGRAMMED											
Z plunge	mm	-2.45	-2.55		-2.45						
Z Plunge feedrate	mm/min	50									
Z Disp or Load		Disp									
Plunge spindle speed	rpm	1300	1200								
plunge entry dwell	sec	1		1.5		2					
Weld 1 feedrate	mm/rev	0.4			0.45		0.3/0.5	0.3			
weld 1 spindle speed	rpm	1200									
SET PARAMETERS											
Spindle Direction	std										
4th axis backward tilt a	1.5	Deg									
TOOLS											
Professional											
SECURITY POSN'S											
Plunge Force	kN	6									
Plunge max. force	%	10									
Plunge security Posn	mm	0									
Weld Force	kN	2.6									
Weld max force	%	10									
Weld security posn	mm	-2.9									
WELD LAT POSN	mm	On c/l		0.5 to Extr			On c/l			0.5 to Extr	.75 to Extr
RUN LENGTH	Sht/Lng	Sht							Long	Long	Long

EXCEL TRIAL 3sht2 SUMMARY.xls

6.6 TRIAL 4 Extrusion to Extrusion

This trial consisted of two lengths of extrusion to be welded back to back. Settings were the same as Run 41, which had successfully produced a half metre long weld between extrusion and plate. The same 2.5mm tool was utilised as it was felt that the extrusion/extrusion weld condition would not be significantly different. The components were clamped laterally as illustrated in Figure 33, and the optimum result, which was Run 42B with a rating of 9/10, is shown in Table 21 along with an image of the weld. The full results of TRIAL 4 are shown in Appendix 4.

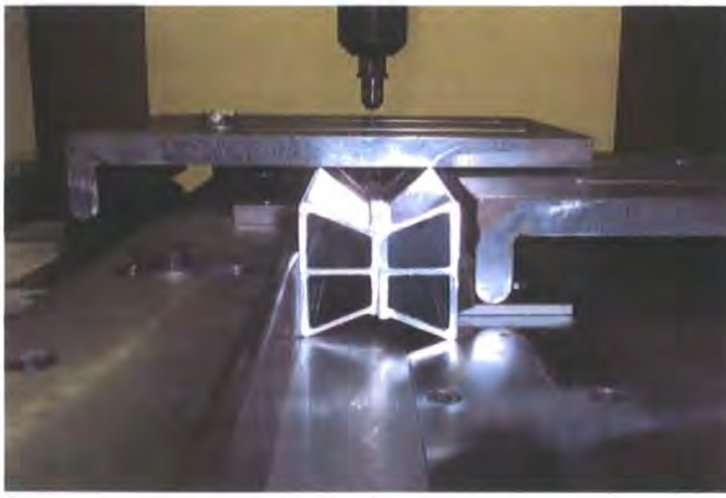


Figure 33 - TRIAL 4 Clamping Arrangements

Table 21 - TRIAL 4 Development and Optimum Result

Z Plunge	-2.45mm
Z Disp or Load	Disp
Spindle Speed	1200 rpm
Weld 1 Feedrate	0.3mm/rev
Weld Lateral position	On Centreline

6.7 TRIAL 5 Multi-Plate

Trial 5 is a complex plate joint. It is seldom possible or desirable to restrict welds in a design to a maximum of two material thicknesses, and complex joint details often result, with several different thicknesses of materials coming together at a weld node. To simulate this whilst respecting the 2D geometry restrictions, the TRIAL 5 weld design comprised 2 plates of 6mm material 6082 in the T651 condition butted together for centreline welding. Above these plates was laid a third length of 3mm 1050A H14 material. The weld was designed to pierce the top plate and follow the centreline of the lower plates to attempt to join all three components with one weld.

The full results of TRIAL 5 are located in Appendix 5. The optimum settings and image for the first run (Run 50B Rated 9/10) are shown in Table 22, the optimum second run (Run 50 Rated 9/10) is similarly summarised in Table 23.

Table 22 - TRIAL 5 Development and Optimum Result Run 50

Tool Type	Triton Dia 6mm, Plunge Length 5.8mm
Weld Depth	6.2mm
Feed Velocity	1mm/rev
Spindle Speed	1100 rpm
Force Control Limit	30kN

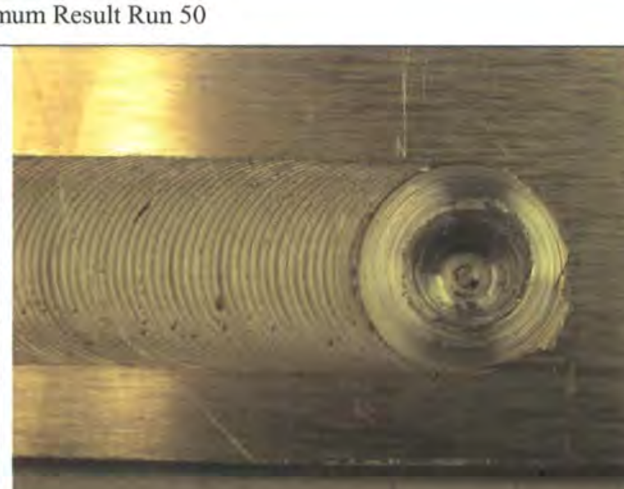


Table 23 - TRIAL 5 Development and Optimum Result Run 51

Tool Type	Triton Dia 6mm, Plunge Length 5.8mm	
Weld Depth	6.2mm	
Feed Velocity	1mm/rev	
Spindle Speed	1100 rpm	
Clamping	Improved	
Force Control Limit	30kN	

6.8 Discussion of Trials

TRIAL 1

The screw-based tool worked effectively at first, and coarse adjustments to travel speed and rotational velocity found a good set of parameters. The fine threads on the screw tool began to block as aluminium present at the end of a run solidified. Despite increasing the 4th axis tilt significantly, little improvement was found until the screw type tool was substituted for a professional tool with coarser threads, which gave an excellent result on the final trial.

TRIAL 2

Initial settings were as previous butt welds, but the results were not similar, the weld appearing cold despite attempts to increase heat with traverse and rotational adjustments. Adjustments to centreline position had little effect. Machine security positions were adjusted to permit greater frictional heat input, but this had to be compensated to prevent excessive tool depth. A final run on unsupported material confirmed the requirement for supporting webs.

It was found that weld support requirements are considerable and must be designed into the extrusion. Machine safety settings can be an integral part of the machine optimisation and must be considered as such for each new setup to give sufficient freedom for the other parameters to be effective. Flatness of the upper weld surface is important when running displacement control as it is not compensated and welds will either become deeper or shallower with flatness variation. If shallower there may be insufficient heat to form a durable weld, if deeper, the weld will be weaker and may be notched. Load control may be more resistant to these issues. It was also noted as a concern that these small welds are close to minimum capability of machine with regard to calibrated control through load cells etc.

TRIAL 3

Settings modified for TRIAL 3 and found to give good welds but with excessive tool depth. When reset to TRIAL 2 settings, welds came closer to a flush condition, improved further with gradual reductions to the Z Plunge Setting. Feedrate was also optimised. Monitoring Load settings showed that the small welds were only generating small loads compared with the machine calibrated range, which may be causing load trips. Weld force limits opened up to counter. Displacement was found to give better control for lighter welds.

TRIAL 4

Clamping was an issue even though the joint appeared straightforward to fixture. The insertion of the tool appeared to force a gap in the plates which closed along the weld length as the heat input increased. This appeared to ease as the weld centreline position was improved. This may be a result of the weld, having been properly formed behind the tool, being sufficiently strong to assist in clamping the extrusions together. It was also noted that immediately after completion; welds with good visual appearance were warm to the touch, cold welds often having a lack of fusion and hot welds having excessive depth or material pick up issues.

TRIAL 5

Considerably more energy was involved which resulted in increased clamping demands. It was found that initiating welds close to the edge of the 3mm plate would cause movement in the unwelded plate as a result of the torque reaction to the weld tool rotation. This then caused a pit in the weld surface as there was reduced material available locally to produce a full weld. It was also observed that with the larger welding tool, the machine was operating further into its operational range. The light welds produced earlier were difficult to run under load control, this heavier weld ran easily under load control.

Overall Conclusion of Trials

Parameters may be determined by experimental means to give a good visual weld condition in a variety of aluminium alloys and joint configurations. Grade and hardness of the alloy was not an observable barrier to welding, and multi-sheet welds were achievable, even with varying grades and material hardness in the same weld. Care must be taken with regards to machine capability for the sizes of welds under consideration, and load or displacement control strategies considered for each different weld type. Tool wear was not observed as an issue in the short samples welded. However the thread of the initial screw-type tool did clog with aluminium, indicating a coarser thread would be beneficial.

Clamping was more of an issue than envisaged, but production clamping may be more sophisticated and dedicated to eliminate the small issues which were encountered. Also, reacting the weld forces was also seen to be important, and sufficient strength must be present in the workpiece to accept these compressive forces.

The trials looked at several possible scenarios for the welding of an extruded suspension arm, and in each case a visually satisfactory weld was rapidly configured. The trials confirmed that fabricating a suspension arm from friction stir welded extrusions is viable, and that it would be worthwhile to progress to a stage where a friction stir welded arm may be welded and assesses by more sophisticated test methods.

7, Evaluation of the Prototype Welds

7.1 Test Sample Selection and Preparation

With the exception of the mechanical testing performed on the initial steel FSW samples, the welding development optimisation had been progressed against purely visual criteria. In order to validate these visual criteria and to determine the performance of the welding, two sample welds from the previous work were selected and mechanical tests were performed.

The components selected for test were the trials where a longer run of weld had been made once the parameters were visually optimized. These were Run 31 from TRIAL 3 (Extrusion to Sheet weld) and Run 51 from TRIAL 5 (Multi–thickness plate weld). In order to reduce the extruded section from TRIAL 3, as may be seen in Table 8, into a flat plate suitable for tensile testing, the extraneous extrusion material was machined away. The mechanical tests selected were: Transverse weld tensile test, Unwelded tensile test, Bending test, Weld sectioning. The two long welded samples were sectioned and four samples cut from each as shown in Figures 34 and 35 to suit the above testing requirements.

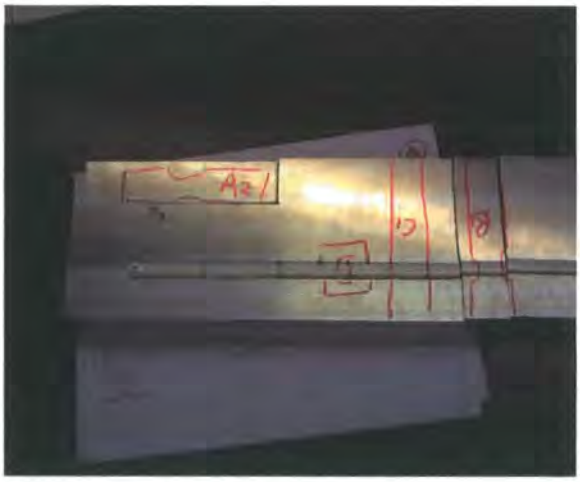


Figure 34 - Sectioning of TRIAL 3 sample

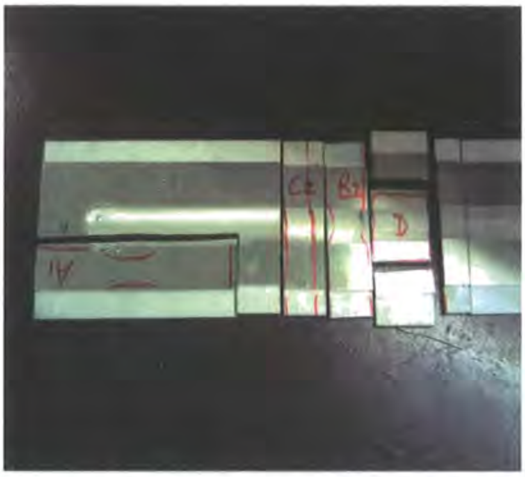


Figure 35 - Sectioning of TRIAL 5 sample

The pieces were identified prior to sectioning as shown in Table 24. It was noted that due to geometrical limitations of the weld samples, the unwelded samples would be cut in a perpendicular orientation to the cross weld samples. The unwelded samples would therefore have been cut along the rolling direction of the material which may have conferred a slight advantage in the tensile tests.

Table 24 - Identification of Test Samples

	Tensile Test Unwelded	Tensile Test Transverse Weld	Bending Test	Cross Section
TRIAL 3 RUN 31	A2	B1	C1 & C3 *	D
TRIAL 5 RUN 51	A1	B2	C2	D
* C1 is with extrusion part-machined away to give a flat plate. C3 is with extrusion				

The sample pieces were then prepared for their individual tests, as shown in Figures 36 and 37. Sample C3 was prepared later as it was considered that partly removing the extrusion may have unnecessarily introduced additional factors into the investigation. A Denison tensile testing machine was utilised for the tensile testing, as shown in Figure 38.

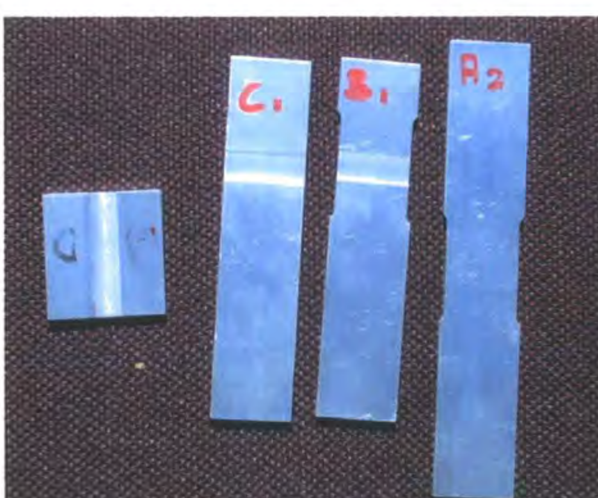


Figure 36 - Test samples from TRIAL 3

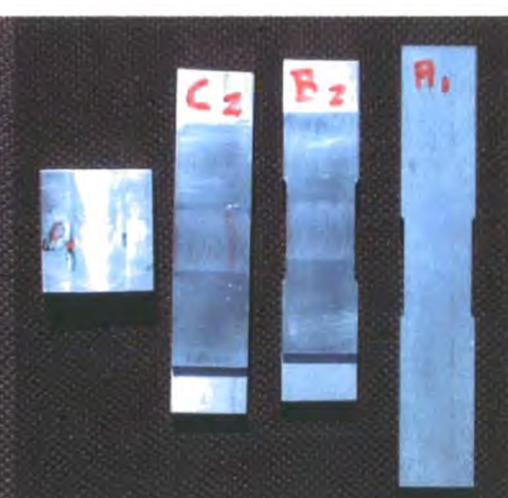


Figure 37 - Test samples from TRIAL 5

Figure 38 - Testing in Denison Tensile Tester

7.2 Tensile Testing: Results and Discussions

TRIAL 3 Tensile Tests

The dimensions of the samples cut from Run 31 of TRIAL 3 and the unwelded sample are given in Table 25. Figure 39 shows the two samples after tensile testing and Figures 40 and 41 present ultimate tensile stress-load curves obtained during the tests. The unwelded sample failed through the centre of the sample but with a shear face set at approximately 10° to the transverse direction. The welded sample failed perpendicularly to the direction of load, and through the stir zone but not the weld centerline. The profile of the sheared surfaces indicated that the failure emanated from the centre of the weld, and not from any notch effects at the edges. The failure load was within 12% of that of the unwelded sample. This deficit reduced if it is considered that the thickness of the sheet was reduced slightly by the welding process. If this is compensated for then the UTS of 206.9 N/mm² for the unwelded sample and 202.2 N/mm² for the welded are within 2.5%. This gives a joint efficiency of 97% which was considered a very satisfactory result.

Table 25 - TRIAL 3 Tensile Test Dimensions and Loads

Sample Number	A2	B1
Thickness	2.88 mm	2.63 mm
Width	25.10 mm	25.15 mm
Maximum Load	14.96 kN	13.38 kN
Ultimate Tensile Strength	206.9 N/mm²	202.2 N/mm²

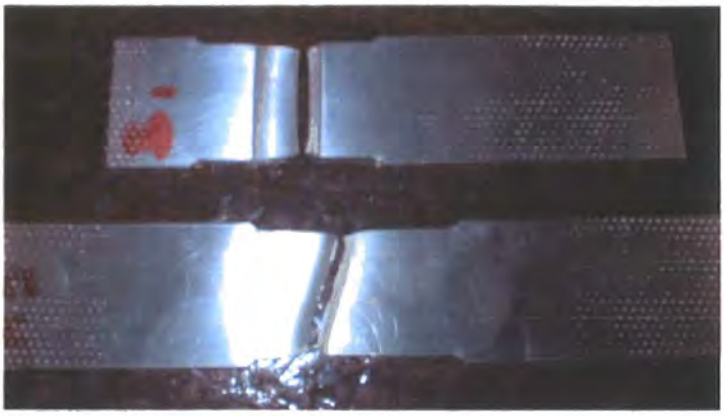


Figure 39 - TRIAL 3 Tensile Samples Post-Test

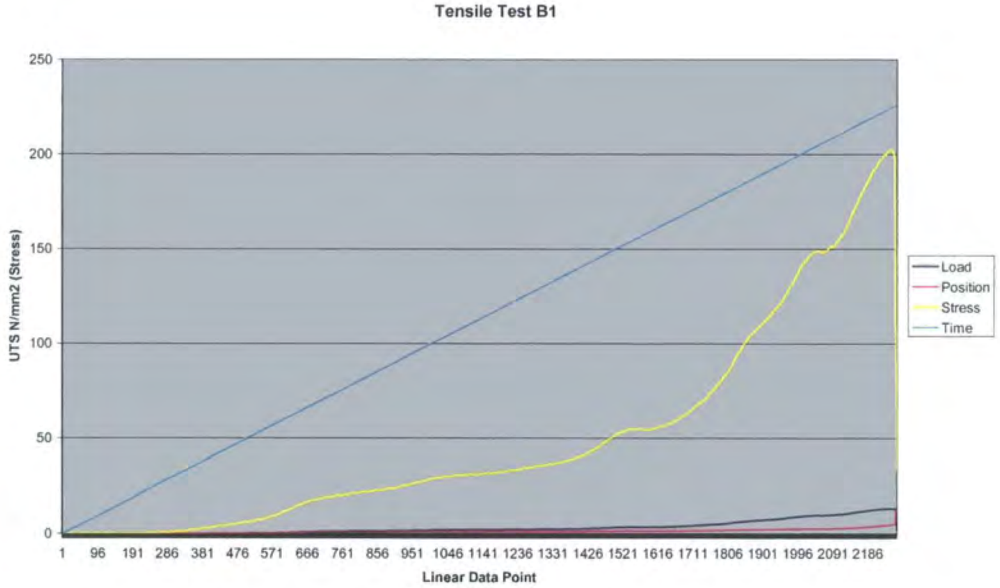


Figure 40 – Results of TRIAL 3 Tensile Test across Weld

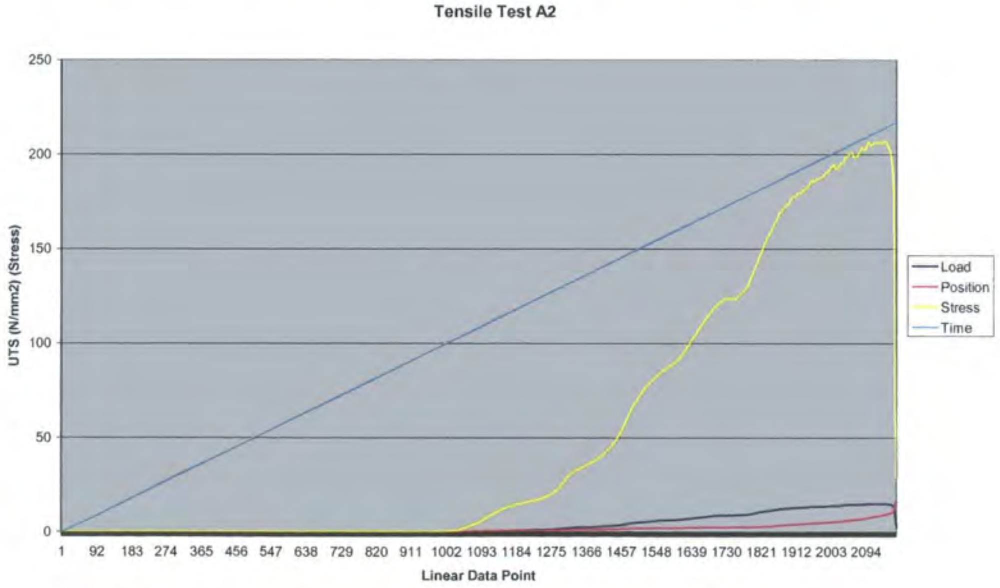


Figure 41 - Result of TRIAL 3 Unwelded Tensile Test

TRIAL 5 Tensile Tests

The results of samples cut from RUN 51 of TRIAL 5 and the unwelded sample are given in Table 26 and test results are shown shown in Figures 42 to 44. The unwelded sample failed irregularly across the sample at 55.33 kN. The welded sample ostensibly failed at 25.43 kN, or approximately half the load of that of the unwelded sample. However, the UTS calculation considered that the cross sectional area of the welded sample was effectively thicker due to the added plate, therefore it further reduced the performance of the welded sample against the unwelded one. It may be argued that the cross sectional area should remain as the thickness of the primary plate, but even so a 50% deficit in performance is evident. Given the excellent performance of the TRIAL 3 result above, reasons were considered for the reduced performance of the TRIAL 5 sample. One consideration was the difference in material grades and therefore properties between the 6mm and 3mm plates, another reason may be due to the lack of the effective depth of penetration of the tool. It is known that plastic deformation and mixing take place below the plunge depth, but the exact amount must be established for each application. A balance must be struck between achieving full weld penetration and preventing welding the workpiece to the backing bar, which may occur if the tool depth is excessive. To avoid this, the tool utilised for this trial was selected with a relatively short plunge depth of 5.8mm. In this case it is likely that the tool depth has been conservative, and a level of effectively cold lap or fully non-joined material will be present in the weld. Data provided by the Weld Section Test was capable of confirming this. If this was the case, then the deficit in performance may be explained as the cross-sectional area will be reduced and a notch will be produced which will further decrease the failure load. Subsequent trials would then iterate through increasing pin lengths to discover the optimum.

Table 26 - TRIAL 5 Tensile Test Dimensions and Loads

Sample Number	A1	B2
Thickness	6.56 mm	9.59 mm
Width	25.16 mm	25.15 mm
Maximum Load	55.33 kN	25.43 kN
Ultimate Tensile Strength (based on overall section thickness)	335.2 N/mm^2	105.4 N/mm^2

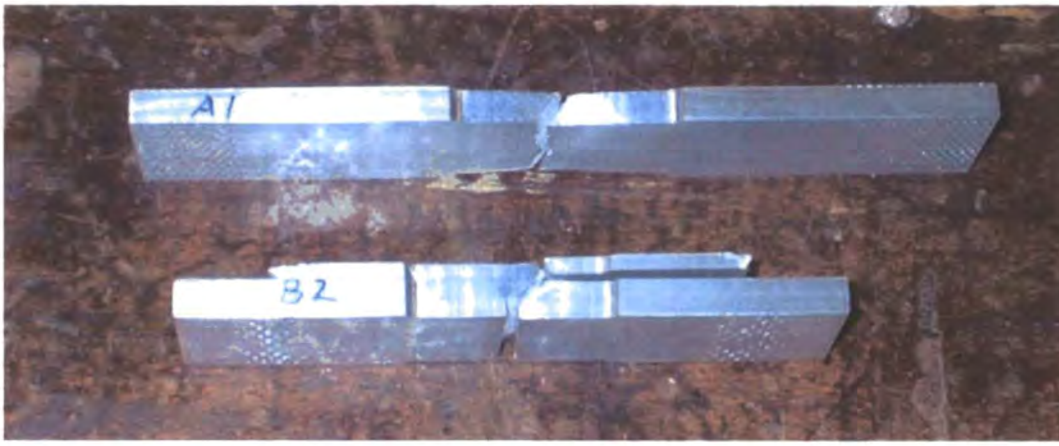


Figure 42 - TRIAL 5 Tensile Samples Post-Test

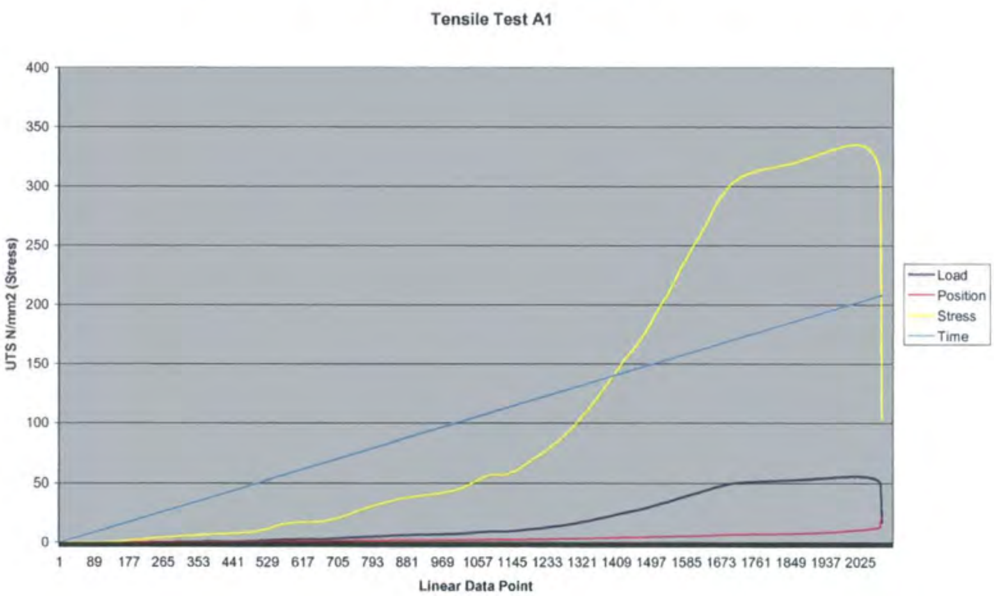


Figure 43 - Result of TRIAL 5 Unwelded Tensile Test

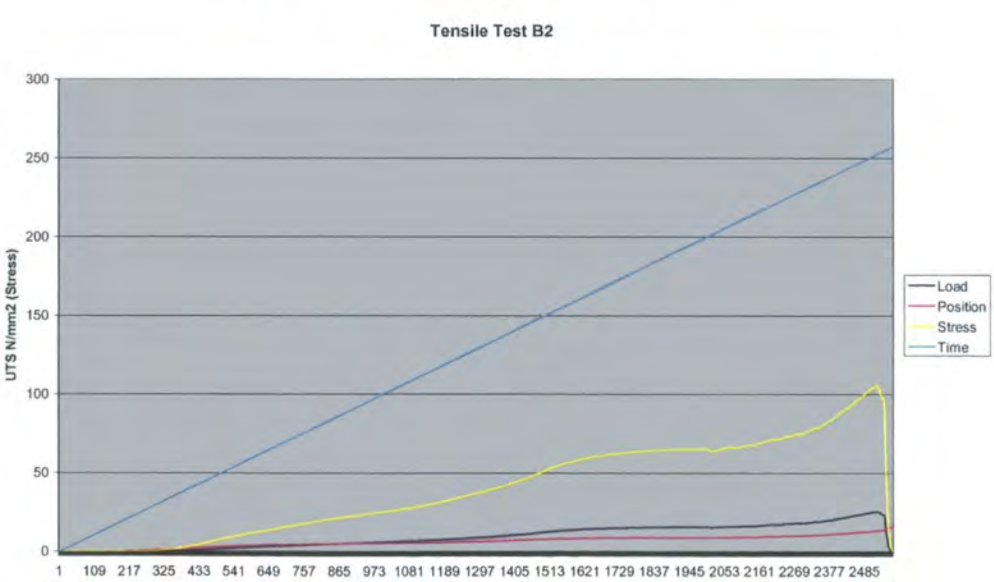


Figure 44 - Results of TRIAL 5 Tensile Test across Weld

7,3 Bend Testing: Results and Discussions

Three samples have been tested, TRIAL 3 samples with the extrusion cut away to form a flat plate (C1) and with the extrusion intact (C3). Also a TRIAL 5 sample with two sheets of 6mm material joined through a 3mm sheet material (C2). The samples were set up in single point bending with the loads and displacements measured in mv and converted through the Load Ring and Displacement Constants into Load and Displacement.

The Bending Test setup and the results of the the TRIAL 3 sample with the extrusion cut away (C1) are shown in Figures 45 to 47 and Table 27, the achieved load is 109 N. A bending stress of 187.5MPa is calculated based on the load obtained and the cross-sections measured, as shown in Table 30. Another sample taken from a different location and with the extrusion intact (C3) was also tested, as shown in Figures 51 to 53 and Table 29, the achieved load was 87 N. However, but when the calculation (details given in Table 30) had compensated for differences in sample width and moment, the stress was similar to the C1 sample at 183.1MPa. This indicates that the weld quality was consistent and the removal of the extrusion had had little effect. The average stress between the two samples, at 185.3 MPa may be compared with the 262 MPa UTS of the 6005a T6 treated extrusion, and the 145 MPa UTS of the 1050A H14 sheet. As the extrusion basically formed only the anchor for the bending of the sheet material, the results obtained were highly satisfactory considering the modest specification of the sheet material; the joint efficiency being over 100%.

The bending test setup and results for the TRIAL 5 sample are shown in Figures 48 to 50 and Table 28. The sample was mounted such that the load opened a gap between the materials, on this basis the beam was calculated with a nominal 6mm thickness, neglecting the attached. 3mm sheet. This loading direction would also stress any lack of joining in the weld root in compression, mitigating any lack of root fusion which may have existed. The maximum load of 620 N calculated to a stress of 278.8 MPa, which when compared to the UTS of 310 MPa for the Grade 6082 T621 material utilised for the 6mm plate, gives a joint efficiency of 90%.

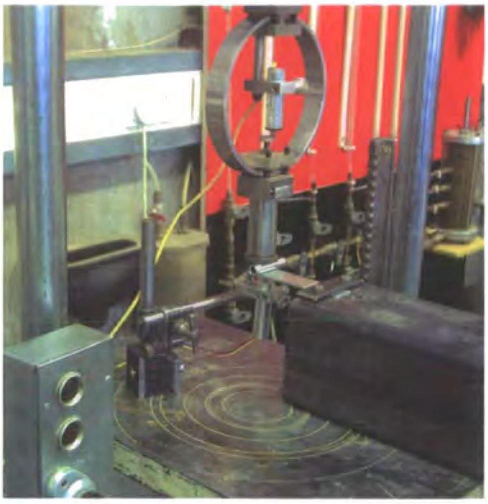


Figure 45 - TRIAL 3 Bending Test Setup

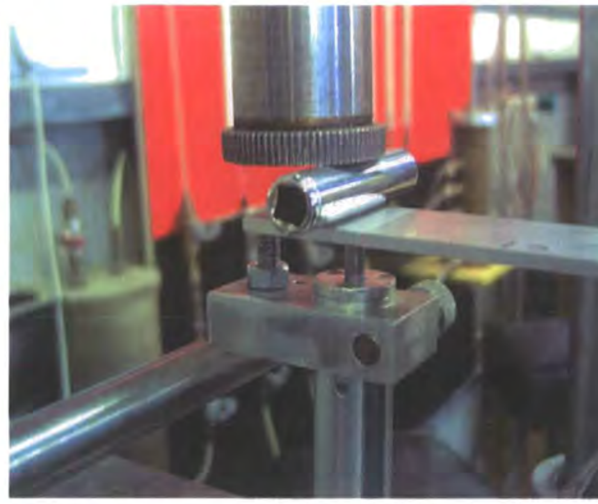


Figure 46 - Loading Details for TRIAL 3 Bending

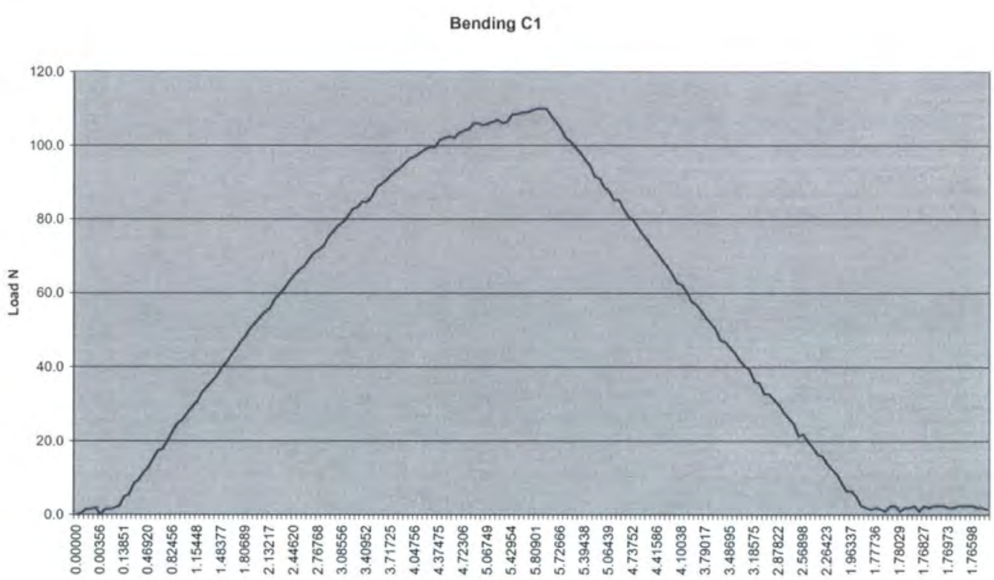


Figure 47 - Result of TRIAL 3 Bending Test

Table 27 - TRIAL 3 Bending Test Dimensions and Loads

Sample	C1
Thickness	2.91 mm (2.52 mm at weld)
Width	28.04 mm
Clamping Point to Loading Point	68 mm
Load Ring Constant	0.4975013 N/mv
Displacement Constant	0.000763143 mm/mv

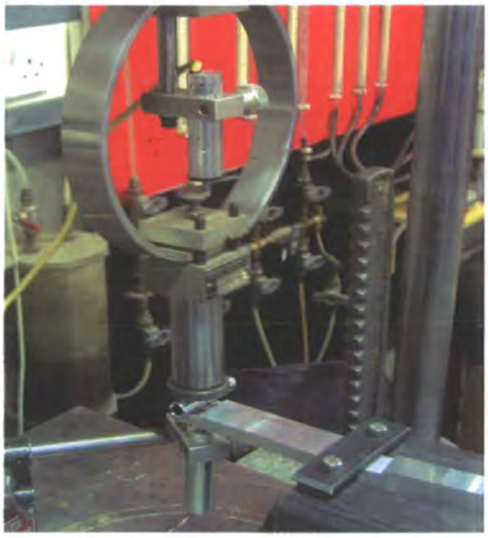


Figure 48 - TRIAL 5 Bending Test Setup

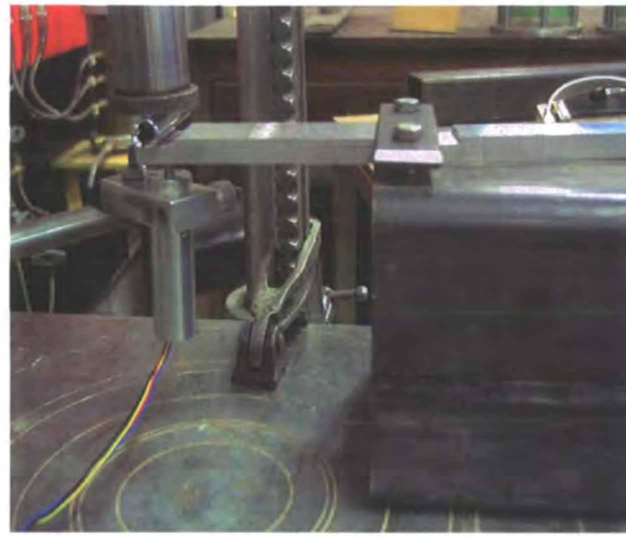


Figure 49 - TRIAL 5 Bending Test Under Load

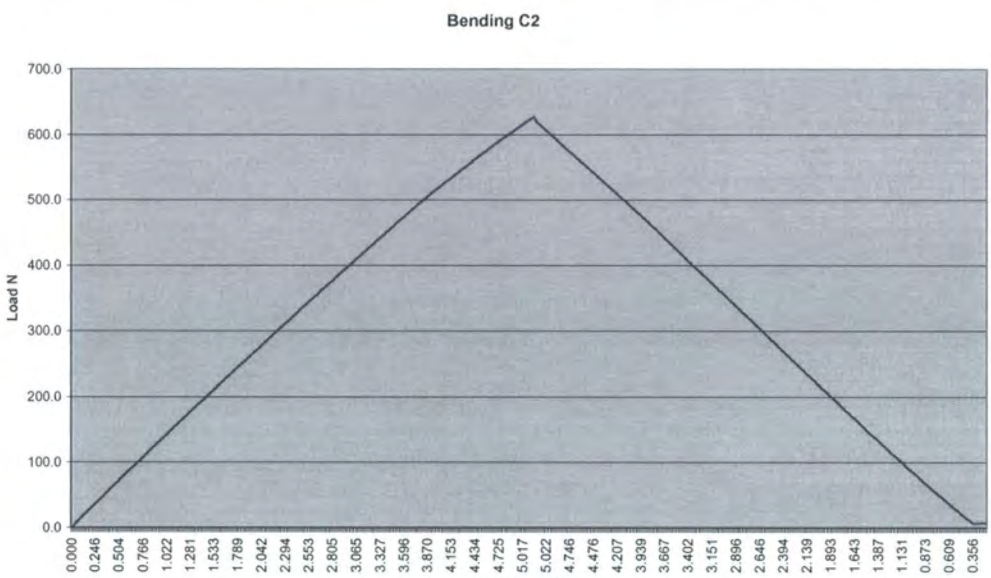


Figure 50 - Result of TRIAL 5 Bending Test

Table 28 - TRIAL 5 Bending Test Dimensions and Loads

Sample	C2
Thickness	9.53 mm & 6.62 mm
Width	28 mm
Clamping Point to Loading Point	90 mm
Load Ring Constant	0.4975013 N/mv
Displacement Constant	0.000763143 mm/mv

Figure 51 - TRIAL 3 C3 Bend Test

Figure 52 - TRIAL 3 C3 Extruded Bend Test Under Load

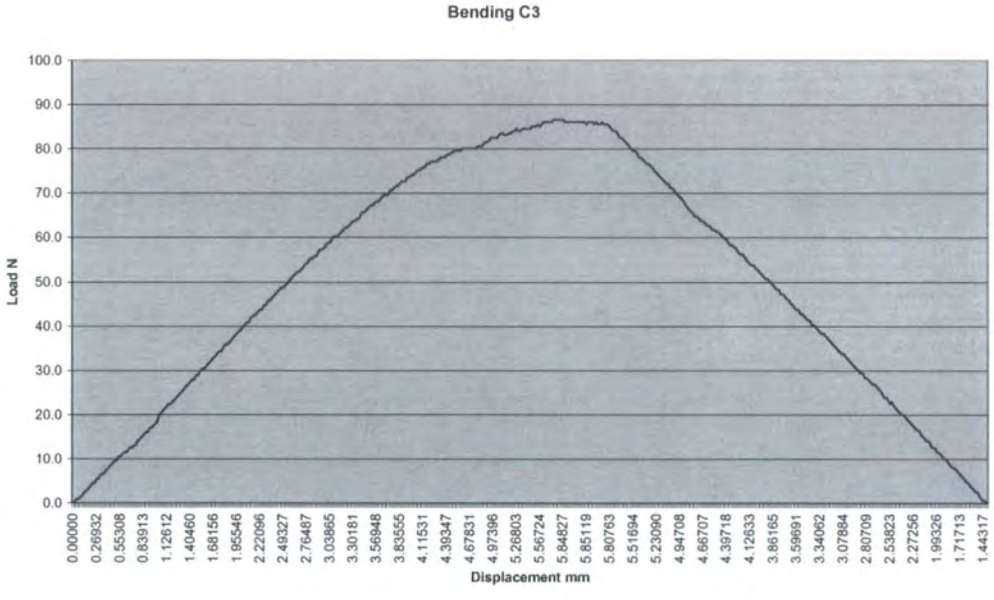


Figure 53 - Result of TRIAL 3 C3 Bending Test

Table 29 - TRIAL 3 C3 Bending Test Dimensions and Loads

Sample	C3
Thickness	2.91 mm (2.52 mm at weld)
Width	26.23 mm
Clamping Point to Loading Point	78 mm
Load Ring Constant	0.4975013 N/mv
Displacement Constant	0.000763143 mm/mv

Table 30 - Bend Testing Calculations

For Bending Test on TRIAL 3 sample, C1 (extrusion cut away):
Neglecting thinning local to weld.
$I = bd^3/12 = 0.028 \times 0.00291^3/12 = 5{,}57 \times 10^{-11}$ m4
M = FL = 109 N x 0.068m = 7.41 Nm
$\sigma = My/I = 7.41 \times 0.001455 / 5{,}57 \times 10^{-11} =$ **187.5 MPa**
For Bending Test on TRIAL 5 sample, C2:
Additional 3mm plate neglected as bending direction away from additional material.
$I = bd^3/12 = 0.028 \times 0.00662^3/12 = 67.7 \times 10^{-11}$ m4
M = FL = 620N x 0.090m = 55.8 Nm
$\sigma = My/I = 55.8 \times 0.00331 / 67.7 \times 10^{-11} =$ **272.8 MPa**
Bending Test on TRIAL 3 sample, C3:
Neglecting thinning local to weld
$I = bd^3/12 = 0.02623 \times 0.00291^3/12 = 5{,}386 \times 10^{-11}$ m4
M = FL = 87 N x 0.078m = 6.78 Nm
$\sigma = My/I = 6.78 \times 0.001455 / 5{,}386 \times 10^{-11} =$ **183.1 MPa**

7.4 Sectioning of the Weld Samples

Two weld sections were taken, one from the TRIAL 3 C1 sample, and one from the TRIAL 5 Multi-thickness sample. The TRIAL 3 section, as may be observed in Figure 54, shows a full thickness weld, with no root flaw, although there is some loss of thickness from 2.91 to 2.52mm due to tool penetration into the top face and minor misalignment of the top face of the extrusion with the top face of the sheet material. The lack of a root flaw is consistent with the good results found from the mechanical testing of this weld.

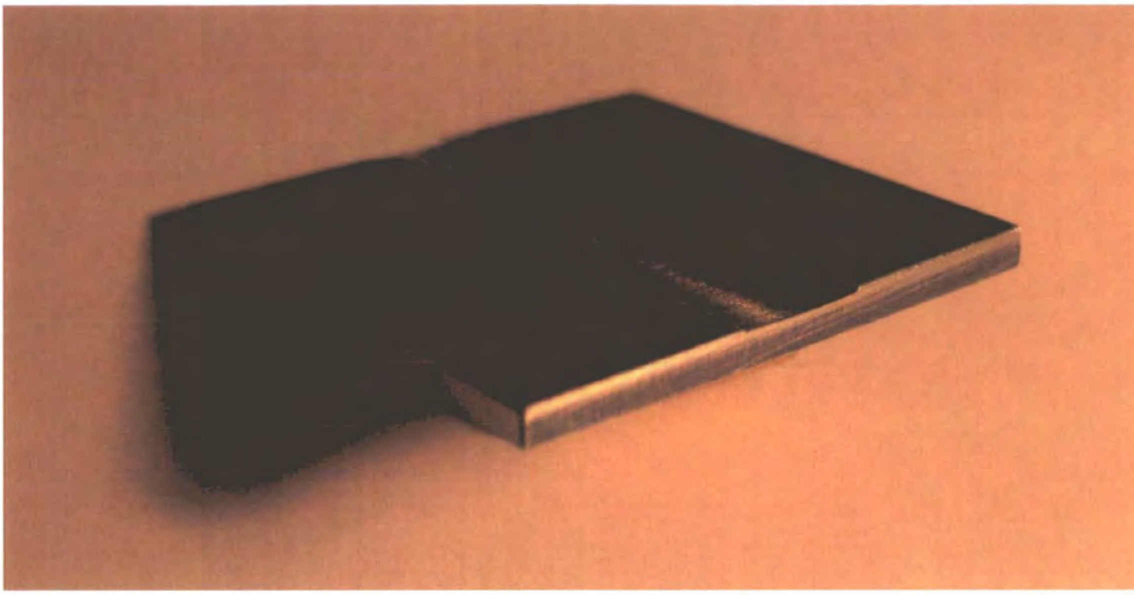


Figure 54 - Section of C1 Weld from TRIAL 3

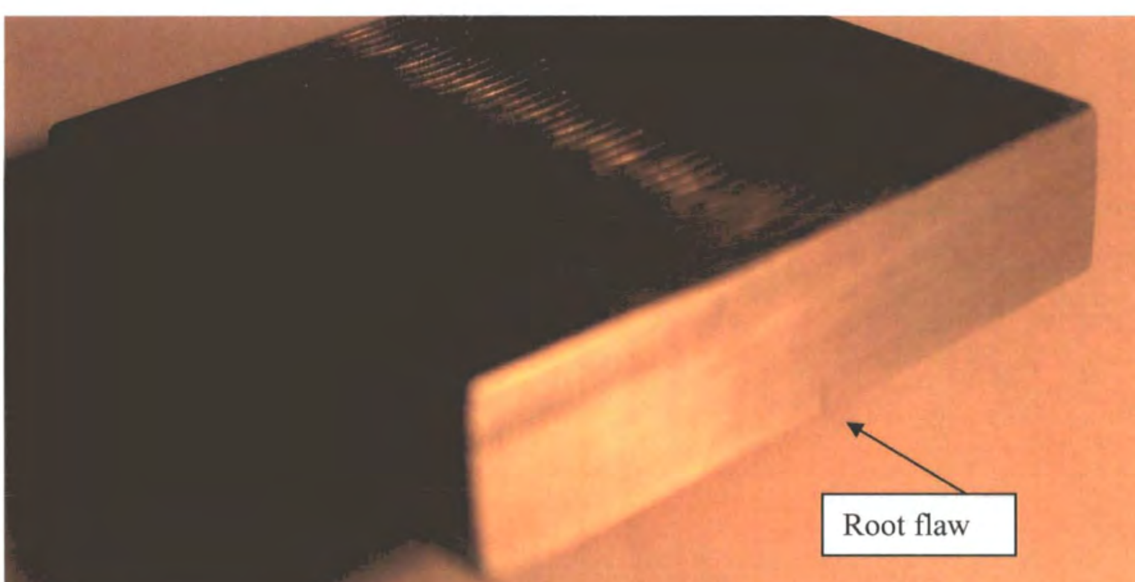


Figure 55 - Flawed Section of C2 Weld from TRIAL 5

Figure 56 - Unflawed Section of C2 Weld from TRIAL 5

The result of the TRIAL 5 Multi-thickness sample showed a flush upper face, with no tool erosion into the sheets. In the section shown in Figure 55 a root flaw is visible to a depth of 2.5mm. In Figure 56, from 40mm further along the weld, the other face of the sample exhibits a good weld. This variability would be sufficient to explain the low failure load exhibited on the tensile test for this sample, where the flaw when present would both reduce the cross sectional area and produce a notch from which a failure crack would easily propagate. This defect would have only a minor effect when in compression, again explaining why the bending test result was superior to that of the tensile test. Any further weld testing would include an optimisation process to ensure the ideal selection of tool depth. In summary of the mechanical testing, the capability of the process was proven, but care must be taken with tool depth to ensure through thickness weld penetration.

7.5 Comparison of Results with Published Work

A paper by Gerceckioglu (46) describes the utilization of a milling machine to circumferentially join aluminium pipe of grade 6063-T6. The pipe was 110mm diameter and 5mm in thickness. Optimum parameter settings were found to be 710 or 900 rpm with a travel speed of 4.94 mm/sec. Initially, the weld was unsupported on the inside, but, as was found on TRIAL 2, reaction force is necessary, and this was added to the bore of the pipe. The temperature at the outer surface of the pipe varied from 195°C to 331°C dependant upon rotational and linear tool speed. The tool contact dynamics were different as the contact surface was curved, which would reduce the heat input unless compensated by a larger diameter shoulder. Again, the importance of correct pin length was highlighted, with root flaws present inside the pipe up to 0.7mm deep due to a perceived lack of pin length.

Definition of a safe process window for FSW of Aluminium sheets was described by Dubourg (47). The area of interest covers the optimisation of FSW of 8mm 6061-T6 plates utilising Taguchi Design of Experiment Methods which had been proposed to optimise the two-sided Steering Arm welds at the prototype stage. This optimisation method is based on an orthogonal array and will determine the optimum parameters with less iterations than a factorial technique. For the 6061-T6 trial, the welding speed was the main predictor of yield strength, but a complex relationship was found between the UTS and the effects of a high number of input parameters.

A paper by Hashimoto (48) studied the bending properties of Aluminium FSW joints between 8mm thick 5083, 6005 and 7204 Alloys. 5083 parent material joints were found to bend to a minimum radius of 4t, 6005 joints to 5.1t and 7204 to 6.8t. For the 6005 alloy, cracking in the HAZ (Heat Affected Zone) were observed.

8 Conclusions

The case for continued lightweighting of vehicles generally has been proposed, with the additional benefits for chassis lightweighting being expounded. A review of current state of the art in chassis structural technology has been developed, with a benchmarking study illustrating the ideal current components, and the choices which the designer must make to achieve an optimum design. Lightweighting opportunities which would also accrue from improved corporate organisation have been explored, as well as lessons to be learned from parallel engineering and construction sectors.

A wide range of relevant materials, manufacturing processes and fabrication technologies have been researched, and any reasons for their unsuitability to be considered for future lightweight applications in their current form explained. Several new combinations of materials, processes and fabrication methods have been offered as solutions, with one specific option of aluminium/extrusion and friction stir welding designed and developed to fruition at the CAE level. Welding trials have ensured that several joint configurations which may be necessary to support this technology can be satisfactorily achieved. The arm design concept is considered feasible for prototype manufacture and subsequent full scale test evaluation.

Following the identification of the 6 point Development Plan, the outcomes were reviewed against the targets:

1, Identify the need

The advantages of a lightweight design on vehicle performance and emissions were illustrated, and comparisons made with other areas of the vehicle where lightweighting has been successful. It was shown that additional benefits derive from suspension lightweighting due to the dynamic nature of the component. Additional energy is saved, and benefits to handling and ride accrue also. The relevance of the research as required by the Development Plan has been satisfied.

2, Benchmarking

Benchmarking of vehicles was undertaken from the year 2000 onwards, concluding that in terms of emissions, improvements in aerodynamics has partly masked the weight increase of vehicles under cruising conditions. However in urban conditions, the increased mass requires increased fuel consumption and therefore emissions which would reduce with lightweight designs. Previous chassis lightweighting studies were critiqued.

Benchmarking studies were carried out on 13 current comparative suspension arms, and conclusions made, particularly with regard to their lightweighting efficiency. Aluminium was identified in forged form as the lightest solution but with associated cost increases. Steel arms were identified as two basic populations and their advantages compared. The benchmarking has met the requirements of the Development Plan in both areas: Vehicles and Components.

3, Limitations

Limitations in current practice were identified in the mainstream areas of Materials and Joining, and also in the areas of geographical integration of manufacturing, value engineering and minimisation of lifetime weight and cost. Examples were given to illustrate each limitation, with proposed changes to improve the situation.

Current materials and manufacturing technologies were investigated and limitations discussed. Developments offering future benefits were identified. The example of cycle frames was explored to illustrate design limitations and comparisons in a conceptually similar product which is also balanced between steel and aluminium solutions.

Joining Technologies were also researched and limitations were identified, particularly with regard to the problems implicit in the ubiquitous use of MIG and spot welding of Steel and Aluminium. Surface technologies were considered both with regard to their improvement to offer better protection to thinner gauge steel and also to gain added value and performance by utilising the soldering effect of hot dip galvanising. The Development Plan required limitations to be sought and significant limitations have been revealed in current practice.

4, Propose Solutions

A range of lightweighting strategies for steel and aluminium were proposed. Materials and manufacturing technologies were considered together. Several High Strength Steel solutions were developed, along with Aluminium in extruded form.

Due to the limitations of current joining technologies, FSW was proposed as the joining method for aluminium extrusions. The use of FSW in other industry sectors was investigated and found to have been accepted in a variety of advanced applications. The Development Plan required that solutions be sought, and a range of solutions encompassing different materials, processes and surfaces have been proposed.

5, Joining Trials

Initial FSW trials were performed on steel coupons, which reinforced the researched position that a feasible production solution for FSW of steel was awaiting further developments in tool materials. The FSW trials of aluminium were considerably more encouraging, with successful joints being performed on sheet and extruded samples despite limited experience of the technology. Successful joints were made between hardened and unhardened alloys of different compositions which would not have been feasible by MIG welding.

Welding trials were proposed by the Development Plan to cover different materials and joint configurations, and these have been successfully completed. The weld development process was by visual assessment, but subsequent successful laboratory testing with a limited range of samples confirmed that the process offered considerable advantages for this type of product over conventional joining technologies.

6, Design

It was decided to select extruded aluminium as the material and manufacturing process respectively for the design concept, with FSW as the joining process. Several iterations of design were proposed and analysed to find the optimum balance between extrusion size and quantity of welding. One, Four and Five piece designs were considered before accepting a Three piece design as the optimum result. The benefits of FSW permitted high strengths to be specified for the extrusions which were not sacrificed in the subsequent welding process. This would have been the case with MIG. Simultaneous double side welding was also proposed to halve the cycle time and cancel reaction stress. Production planning was also considered, with a manufacturing strategy considerably simpler than a conventional steel pressed solution, and with reduced process variation.

The design was considered to have satisfied the target requirements when assessed in the virtual world as required by the Development Plan. In comparison to the control design, the final developed design offered a weight reduction of 27.6% with a beneficial stiffness increase of 118% whilst maintaining a safety factor of 17% over the Maximum Design Stress.

Subsequent Activities (post-thesis)

No issues were found which may indicate that the proposed design was not feasible, and it would therefore be appropriate to proceed with the prototype and test evaluation stage as proposed in the Development Plan. In addition to the mainstream design work, it was considered that two other areas have potential as lightweight solutions and are proposed for identified for further development:

Friction Stir Spot Welding as an enabler for High Strength steels. As FSSW has a less detrimental effect on material properties in comparison with fusion spot welding, a greater percentage of the high strength is preserved after fabrication, permitting a lighter gauge material, which confers a lighter weight design. Hot dip galvanising may also be developed to both give increased protection to the thinner gauge steel whilst simultaneously adding stiffness through soldering to the flanged joints.

Utilisation of large squeeze cast castings in conjunction with extrusions to form larger structural components such as subframes. It is envisaged that FSW would be capable of joining squeeze castings to extrusions with minimal loss of properties at the weld.

9 References

1, Dawson, S; Schroeder, T. Practical Applications for Compacted Graphite Iron. Transactions of the American Foundry Society and the One Hundred Eighth Annual Metalcasting Congress; Rosemont, IL; USA; 12-15 June 2004. pp. 813-821. 2004

2, Autocar Annual Reports (2000/2005)

3, American Iron and Steel Institute. Ultralight Steel Auto Suspension (ULSAS) Engineering Report. First Edition. December 2001.

4, Hartley, J. Collaborative Value Analysis: Experiences from the Automotive Industry. The Journal of Supply Chain Management (2000) 36 (4), 27–32. doi:10.1111/j.1745-493X.2000.tb00083.x.

5, Hu, H. Squeeze casting of magnesium alloys and their composites. Journal of Material Science. Springer Netherlands. ISSN 0022-2461 (Print) 1573-4803 (Online) Volume 33, Number 6 / March, 1998

6, Hydroforming Finding New Uses In The Automotive Industry - Brief Article Autoparts Report, Oct 19, 2001

7, Hunter, D. Using Hydroforming aluminium components versus steel stampings. The Tube and Pipe Journal, 15 Nov. 2001.

8, Hirsch, J. Automotive Trends in Aluminum, The European Perspective: Part Two. Hydro Aluminium Deutschland GmbH, R&D, D-53014 Bonn, Germany.

9, Ogando, J. Stronger Steels Create Joining Challenges. Design News, July 7, 2005.

10, Occupational Health Concerns in the Welding Industry. Taylor & Francis Health Sciences. ISSN 1047-322X (Print) 1521-0898 (Online). Volume 15, Number 12. December 1, 2000. DOI 10.1080/104732200750051175. 936-945.

11, Cho, Y. Hu, S.J. Li, W. Resistance spot welding of aluminium and steel: a comparative experimental study. Proceedings of the I MECH E Part B Journal of Engineering Manufacture, Volume 217, Number 10, 1 October 2003, pp. 1355-1363(9) Professional Engineering Publishing.

12, Zhao H. White D.R. DebRoy T. Current issues and problems in laser welding of automotive aluminium alloys. International Materials Reviews, Volume 44, Number 6, June 1999, pp. 238-266(29). Maney Publishing.

13, Feng, Z. Basic studies of ultrasonic welding for advanced transportation systems. Oak Ridge National Laboratory. 2003.

14, Mortimer, J. Jaguar 'Roadmap' re-thinks self-piercing technology. International Federation of Robotics. Industrial Robot Journal Vol. 32 No. 3 2005. ISSN 1043-991X.

15, Rooks, B. Tailor-welded blanks bring multiple benefits to car design. Assembly Automation ISSN: 0144-5154 Dec 2001 Issue: 4 Page: 323 - 329 Publisher: MCB UP Ltd.

16, Pieters, R.R.G.M., Richardson, I.M.Laser welding of zinc coated steel in overlap configuration with zero gap. Science and Technology of Welding & Joining, Vol.10, Number 2, April 2005, pp. 142-144(3). Maney Publishing

17, Van Alsenoy, V. Warichet, D. MICROZINQ D4 - Performance tests on ultra thin batch hot-dip galvanizing. Intergalva 2003: Twentieth International Galvanizing Conference; Amsterdam; Netherlands; 1-6 June 2003. pp. 1-4. 2003

18, Feraboli, P. Masini, A. Development of carbon/epoxy structural components for a high performance vehicle. Department of Mechanical Engineering, University of California, Santa Barbara, CA 93106, USA and R&D Advanced Composites Materials, Automobili Lamborghini S.p.A., Sant'Agata Bolognese 40019, Italy. March 2004.

19, Marzoli, L.M., Zettler, R., Dos Santos, J.F., Volpone, M., Rizzuto, E. Friction Stir Welding of an AA6061/Al_2O_3/20p reinforced alloy. Elsevier Ltd. 29 June 2005.

20, Jones, S., Smith, R. Disruptive Technology. Metalworking Production. August 2005, P19.

21, Webb, P., Eastwoods, S., Jayaweera, N., Chen, Y. Automated Aerostructure Assembly. International Federation of Robotics, Industrial Robot Journal Vol. 32 No. 5 2005. ISSN 1043-991X.

22, Ward, A.C. Toyota's principles of set-based concurrent engineering. Cambridge 1999.

23, Lee, D.C., Lee, J.I. Structural optimisation concept for the design of an aluminium control arm. Proc. Instn. Mech. Engrs. Vol. 217 Part D: J. Automobile Engineering.

24, Reddy, M.P., Baumann, C.E. Computational simulation of friction stir weld processes. 2004 SAE World Congress.

25, Hinrichs, J.F., Noruk, J.S., McDonald, W.M., Heideran, R.J. Challenges of welding aluminium alloys for automotive structures. Svetsaren No. 3, 1995.

26, Kallee, S.W., Kell, J.M., Thomas, W.M., Wiesner, C.S. Development and implementation of innovative joining processes in the automotive industry. TWI, 2005.

27, Young, K., Tuersley, Y., Vaidya, A. UK Robotic installation statistics for 2004. Warwick Manufacturing Group. Feature, Industrial Robot: An International Publication 32/6, 2005.

28, Maddox, S.J. Fatigue design of welded structures. ISBN W1-001-A1009. 1994.

29, Benson P.G. Complex forming of aluminium extrusions. MIRA New Technology publication, 2004.

30, Ericsson, M., Sandstrom, R. Fatigue of FSW overlap joints in aluminium, welded with different tool designs. Royal Institute of Technology, Stockholm. 5th International FSW symposium. 2004.

31, Watts, E.R. Dual rotation stir welding –Preliminary trials. [Online] TWI. 8 April 2004.

32, Thomas, W.M., Sylva, G. Developments in friction stir welding. ASM Material Solutions Conference, Pittsburgh 2003.

33, Smith, C.B. Robotic friction stir welding using a standard industrial robot. Tower Automotive. Milwaukee. Kei Kinzoku Yosetsu. Vol. 42, No. 3, 2004.

34, Bird, C.R. The inspection of friction stir welded aluminium plant. TWI. 5th International FSW symposium. 2004.

35, Bloss, R. Ford welds a winner. Feature, Industrial Robot: An International Journal 32/6 2005.

36, Ellis, M.B.D., Gottos, M.F., Threadgill, P.D., Joining Aluminium Based MMC's. Materials World, Vol. 2. No. 8, pp 415-17 August 1994.

37, Storjohann, D., Babu, S.S., David, S.A., Sklad, P. Friction stir welding of aluminium metal matrix composites. M & C Division, Oak Ridge National Laboratory, Oak Ridge, TN 37831-6096.

38, Thomas, W., Threadgill, P.L., Nicholas, E.D. Feasibility of friction stir welding steel. Science and Technology of Welding and Joining. 1999 Vol. 4 No.6 ISSN 1362-1718.

39, Hirakawa, M., Yamamoto, H., Shinoda, T., Takegami, H. Mechanical properties of friction stir joint for mild steel. 5th International FSW Symposium, 2004.

40, Lienert, T.J., Tang, W., Kuidahl, L.G. Friction stir welding of DH-36 steel. Los Alamos.

41, Kiuru, M. Experimental studies on diamond-like carbon and novel diamond-like carbon-polymer-hybrid coatings. University of Helsinki, 2004.
42, David, S.A., Feng, Z. Friction stir welding of advanced materials: Challenges. Oak Ridge National Laboratory.

43, Fukumoto, M. Butt welding between dissimilar metals by friction stirring. Togoshi University of Technology. 5th International FSW Symposium 2004.

44, Metcalf, K. Embodiment design and finite element analysis of an aluminium suspension control arm suitable for friction stir welding. University of Durham 2005.

45, Crummey, S. Design and finite element analysis of an extruded aluminium suspension control arm. University of Durham 2006.

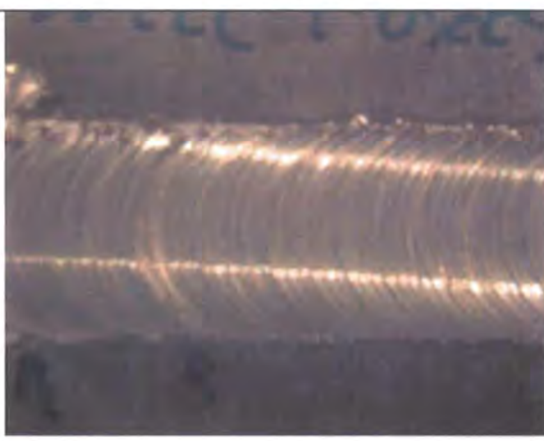
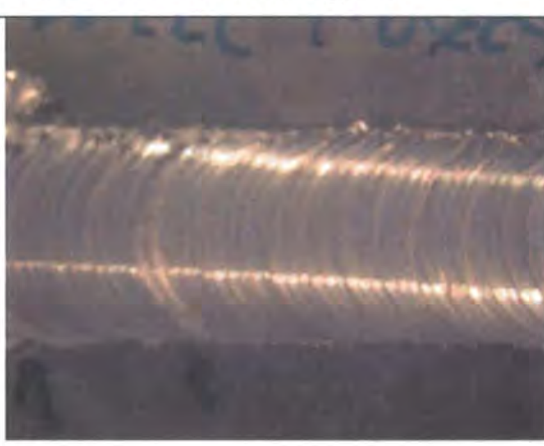
46, Gerceckioglu, E., Eren, T., Yildizli, K., Salamci, E. The application of friction stir welding method to the aluminium alloy of AA 6063-T6 pipe using a milling machine. Erciyes University. Sixth International Friction Stir Welding Symposium. Montreal, 2006.

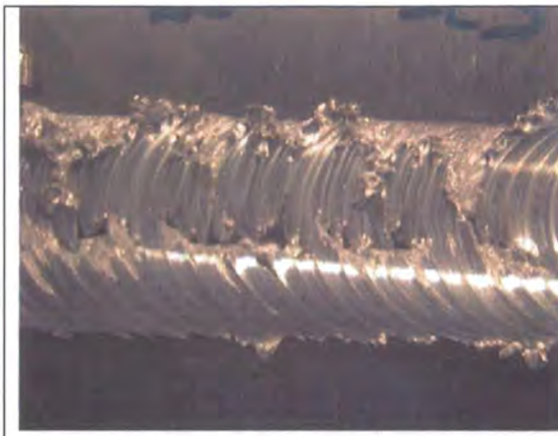
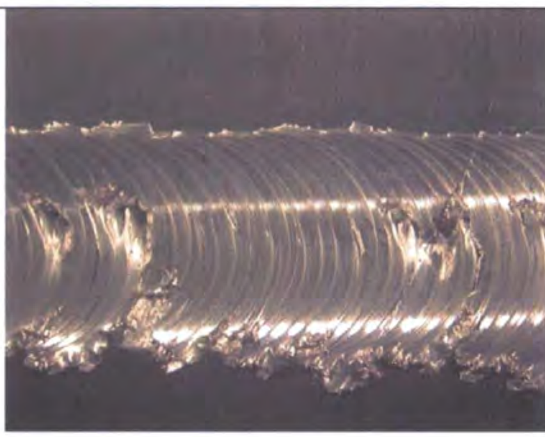
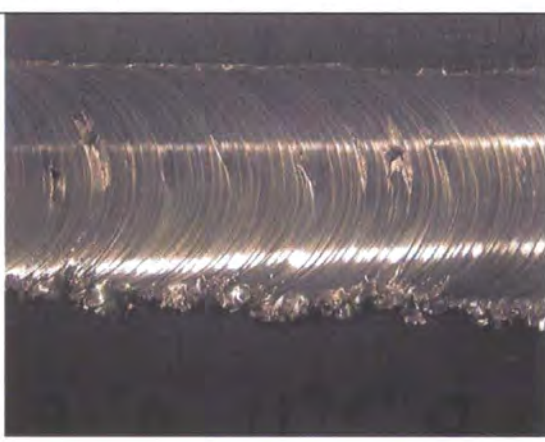
47, Dubourg, L., Gagnon, F.O., Nadeau, F., St-Georges, L., Jahazi, M. Process window optimisation for FSW of thin and thick alloy sheet AL alloys using statistical methods. Aerospace Manufacturing Centre, NRC, Canada. Sixth International Friction Stir Welding Symposium. Montreal, 2006.

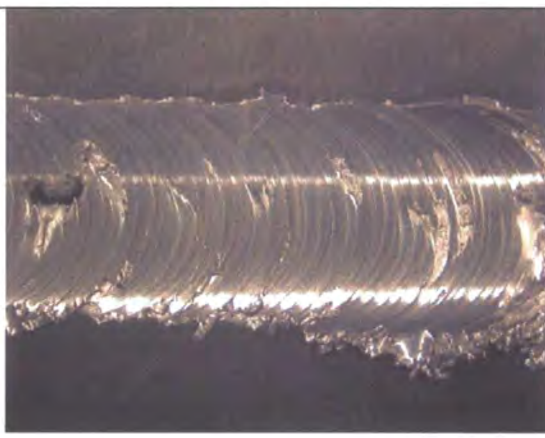
48, Hashimoto, J., Takeda, J., Miyamichi, T., Namba, K. Studies on characteristics of friction stir welded joints in structural aluminium alloys. Part 3: Bending properties of friction stir welded joints. The Japan Light Metal Welding and Construction Association Inc. Welding Procedure Committee, FSW Sub-Committee. Sixth International Friction Stir Welding Symposium. Montreal, 2006.

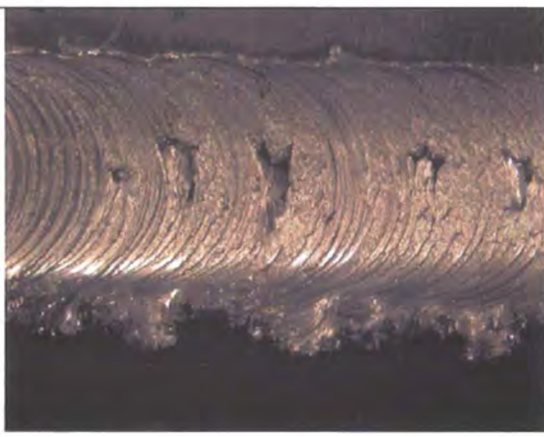
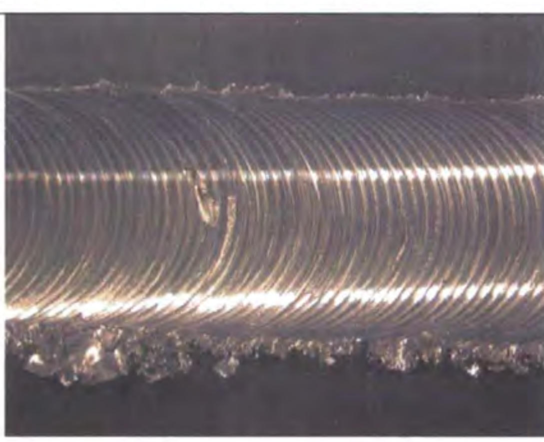
Appendix

Appendix 1 Results of TRIAL 1

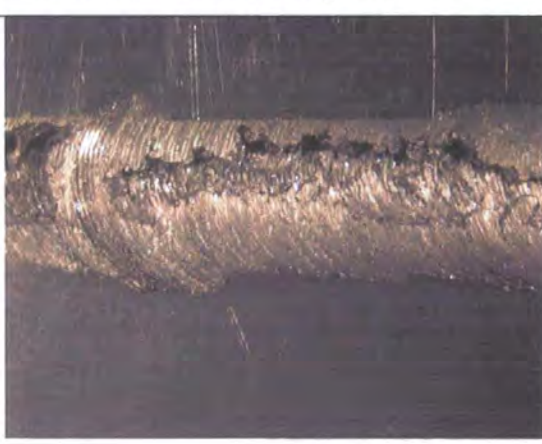
 Visual Assessment Rating 6/10	RUN 1 -Initial Settings Weld appeared to be too hot, and post-weld the aluminium workpiece had adhered to the steel backing plate. The slow travel speed was considered the cause.
 Visual Assessment Rating 8/10	RUN 2 The travel speed was increased from 0.1 to 0.5 mm/rev, which gave a general improvement in weld quality.
 Visual Assessment Rating 8/10	RUN 3 The travel speed was increased again to 1mm/rev, the Plunge Entry Dwell reduced to zero as considered not to be required with small weld cross section. It was considered that sufficient heat was generated to adequately soften, but with some pickup of material.

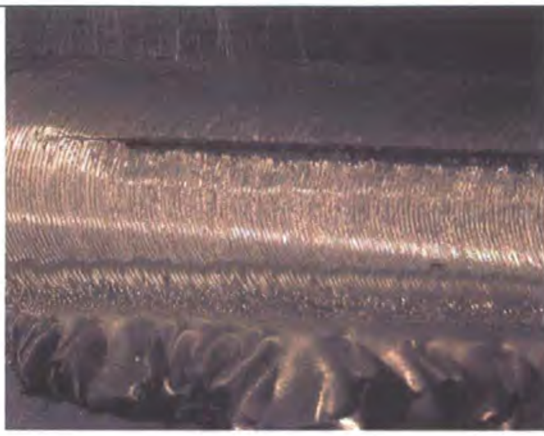
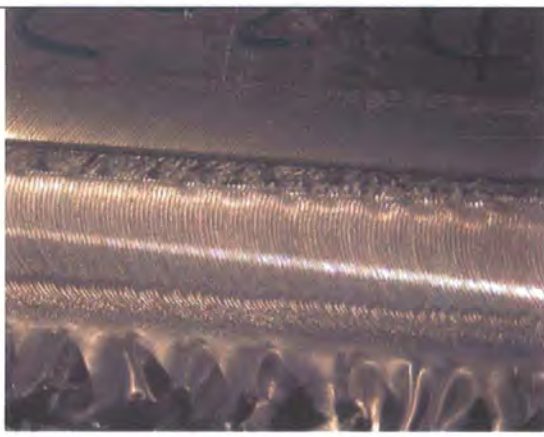
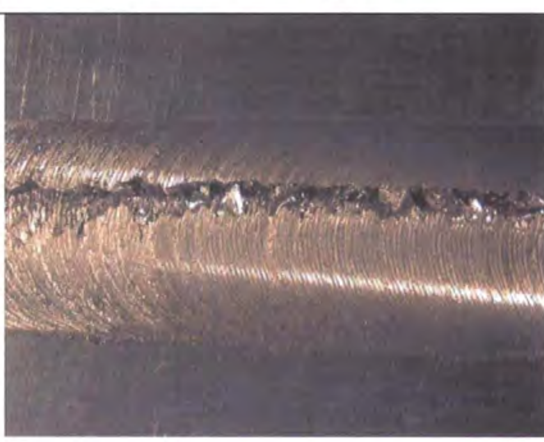
<table>
<tr><td>
Visual Assessment Rating 3/10</td><td>RUN 4
Travel speed decreased to 0.4 mm/rev. in search of an optimum.
Too hot, increased pick-up.</td></tr>
<tr><td>
Visual Assessment Rating 5/10</td><td>RUN 5
Travel Speed increased again to 1mm/rev. as 0.4mm/rev had not been an improvement.</td></tr>
<tr><td>
Visual Assessment Rating 7/10</td><td>RUN 6
Spindle Speed increased from 1100 to 1300 rpm.
Possibly too hot.</td></tr>
</table>

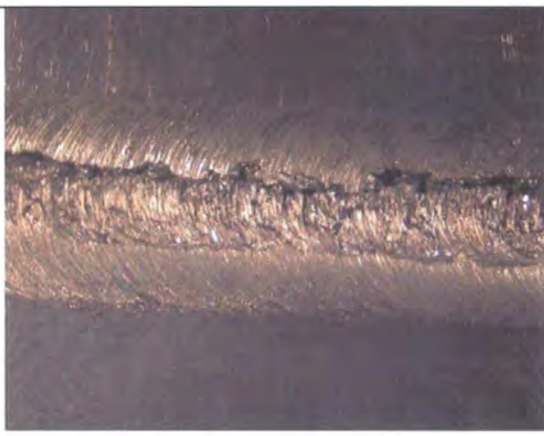
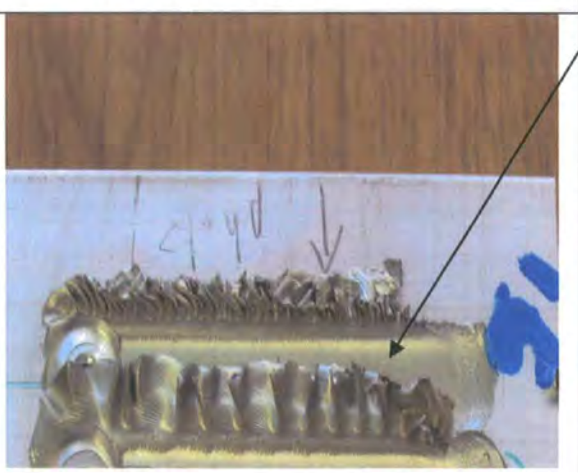
 Visual Assessment Rating 3/10	RUN 7 Travel speed decreased to 0.5mm/min whilst retaining fast spindle speed of 1300 rpm. Weld length reduced from 50 to 40 mm to suit remaining weld length on sample.
 Visual Assessment Rating 6/10	RUN 8 Spindle Speed reduced to 1100 rpm as RUN 2 considered best to date. Weld length returned to 40mm
 Visual Assessment Rating 4/10	RUN 9 Checked tool for cleanliness in light of material pickup. Removed tool for cleaning with caustic soda but not possible to clean adequately. Replaced tool with identical new one. Improved weld.

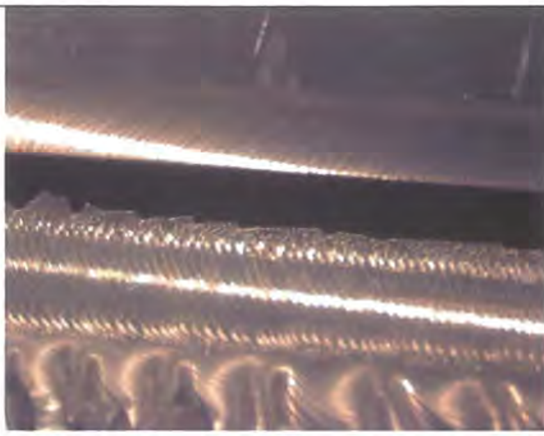
 Visual Assessment Rating 8/10	RUN 10 Reset 4th axis backward tilt from a minimum ideal setting of 0.25° to 1.5° Improved weld.
 Visual Assessment Rating 7/10	RUN 11 Tried replacing with cleaned original tool, slightly worse result than last trial despite better 4th Axis setting.
 Visual Assessment Rating 9/10	RUN 12 Tried professional tool in lieu of previous. Much improved result.

Appendix 2 Results of TRIAL 2

 Visual Assessment Rating 3/10	RUN 13 Settings as RUN 12 with 1 sec delay added to plunge to encourage web to gain heat prior to traverse. Weld was cold.
 Visual Assessment Rating 1/10	RUN 14 Increased rotational speed from 1100 to 1300rpm and reduced feed/rev from 0.5 to 0.2 to generate more heat into the aluminium. Weld still cold.
 Visual Assessment Rating 2/10	RUN 15 Tool depth increased to 1.9mm, still under position control. Concern that usual adjustments were not achieving improvements. Considered if Safety Settings were restricting operation

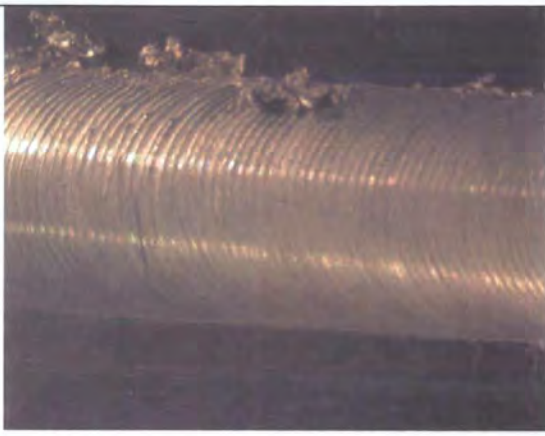
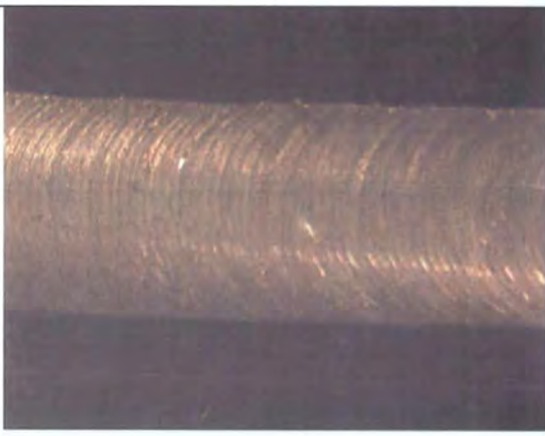
 Visual Assessment Rating 4/10	RUN 16 Weld security position lowered from 2 to 2.4 mm which gave additional margin for tool set depth to operate. Weld force security position tightened from 6 to 3 kN as monitored forces low. Weld much cleaner but has excessive depth.
 Visual Assessment Rating 5/10	RUN 17 Z plunge setting reset to 1.8mm from 1.9mm and Security position on depth reset to 2mm to offset excessive depth. Weld force further reduced to 1.6 kN
 Visual Assessment Rating 4/10	RUN 18 Weld path moved 0.5mm to RHS of tool travel line to prevent centreline cracking due to lack of support. Little change.

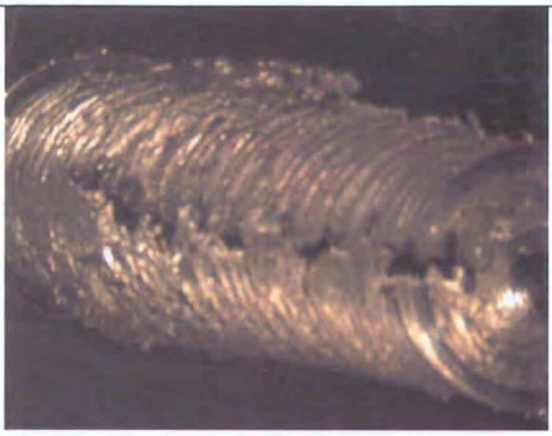
 Visual Assessment Rating 4/10	RUN 19 Weld path moved 0.5mm to LHS off centreline to check for upstream / downstream flow effects. Little difference observed.
 Visual Assessment Rating 4/10	RUN 20 Reset offset to centreline. Result similar to RUN 18 expected and obtained.
 Visual Assessment Rating 8/10	RUN 21 Feedrate increased from 0.2 to 0.4mm/rev to reduce heat input. Security position lowered from 2 to 2.2mm. Best visual condition weld so far, but with excessive depth and swarf.

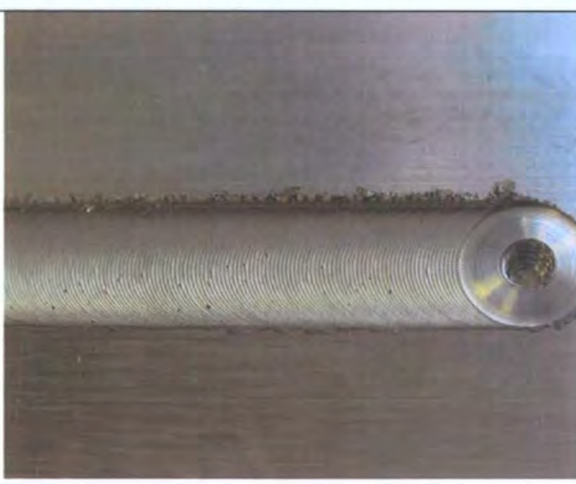
 Visual Assessment Result N/A	ADDITIONAL UNSUPPORTED RUN Additionally a run was made over an unsupported length of extrusion to confirm that the weld metal will be lost without support. This did occur along the weld centreline where higher temperatures would be experienced, but the material under the shoulders remained predominantly in place. Photograph shows a larger scale view of the foreground of the image above.

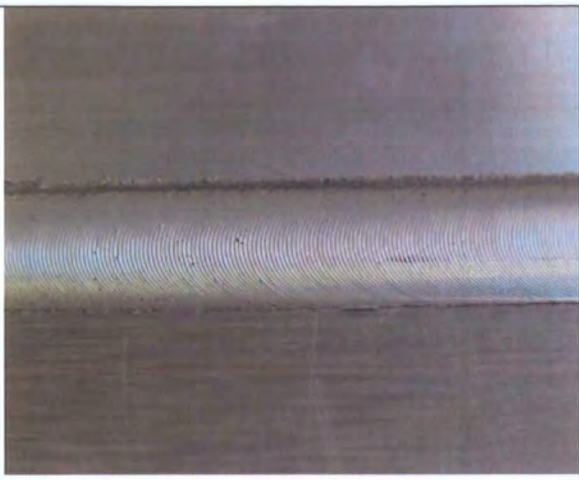
Appendix 3 Results of TRIAL 3

 Visual Assessment Rating 8/10	RUN 22 -Z plunge depth increased from -1.8 to -2.6mm in line with new material thickness. -Plunge and traverse spindle speed increased from 1100 to 1300 RPM to increase heat input. -Feed rate tried initially at 0.4mm/rev -Plunge security position set at 0 from -2mm in conjunction with load control to attempt to limit thinning. Good weld but excessive removal of material. Tripped on excessive load.
 Visual Assessment Rating 8/10	RUN 23 Repeated to check trip-out response. -Z plunge increased from -2.6 to - 2.7mm, -Weld Force security position increased from 2.5 to 2.6 kN. -Weld max force security position % increased from 10 to 20% Same quality weld with excessive material removal. Tripped again.
 Visual Assessment Rating 9/10	RUN 24 Changed to displacement position control in attempt to overcome excessive flash. Z plunge and Weld max force reset to RUN 22 settings. Similar result, minor improvement.

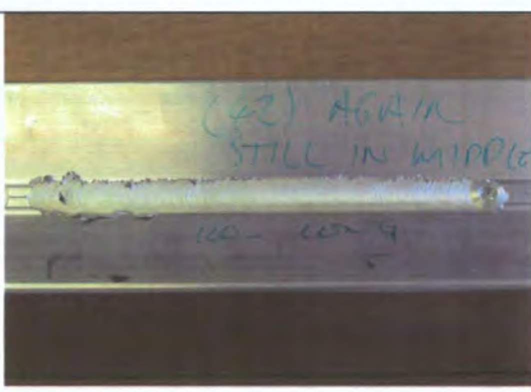
 Visual Assessment Rating 9/10	RUN 25 Z plunge reduced slightly to -2.5mm. Generated excellent weld. Flash considerably reduced.
 Visual Assessment Rating 9/10	RUN 26 Z plunge reduced further, -2.5 down to -2.4 to reduce flash still further.
 Visual Assessment Rating 9/10	RUN 27 Flash had been eliminated fully but weld sides were now parallel, indicating plunge was slightly high and reset to 2.45mm, i.e. half way between the previous two settings. Good result maintained, identical appearance, no flash.

 Visual Assessment Rating 3/10	RUN 28 Run on load control. Tripped again on load as when previously tried on load control. Load cell is measuring approx 1 to 2 kN against 50kN capacity. Load is found to be very low compared with machine capacity and marginal in terms of calibration range.
 Visual Assessment Rating 8/10	RUN 29 Weld security position lowered from - 2.9mm to – 3.5mm Much improved result.
 Visual Assessment Rating 7/10	RUN 30 Z security position reduced to -3mm Tightened acceptable security displacement setting in order to restrict undercut. Weld force limit was opened up fully from 2.6 to 10kN Weld mostly good, excessive flash.

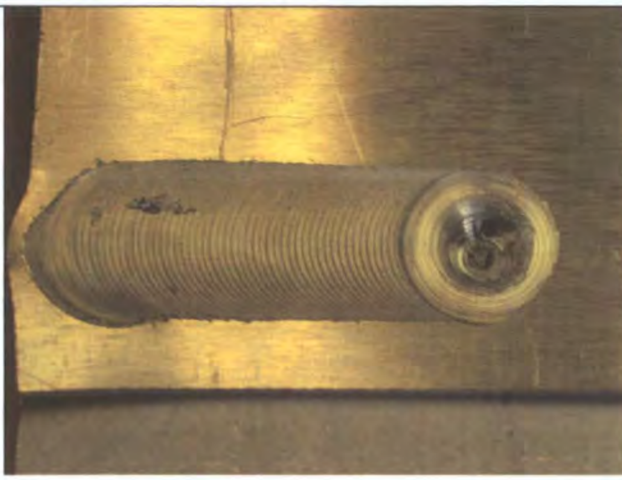
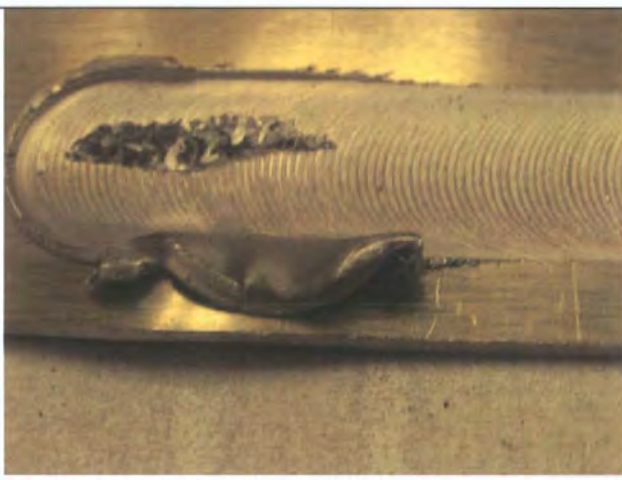
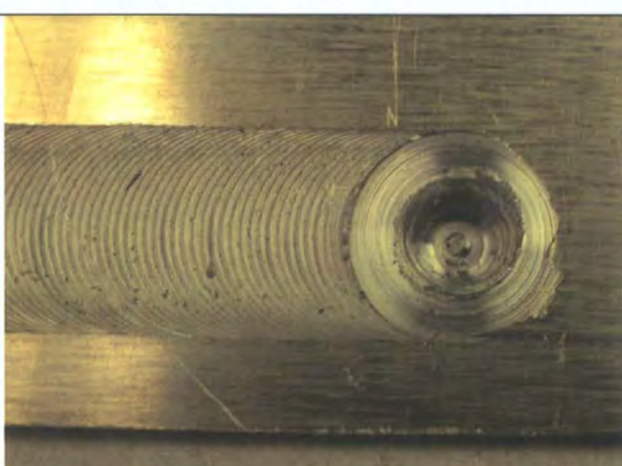
 Visual Assessment Rating 9/10	RUN 37 -New lengths of identical material, unchanged clamping setup. -Set up with two travel speeds in attempt to reduce previous situation where best steady state weld had poor start-up condition. For first 10mm travel speed was 0.3mm/rev, then 0.5mm/rev.
 Visual Assessment Rating 10/10	RUN 38 The overall result of 38 was considered acceptable, but weld path not considered ideal. Determined that two long runs of weld would be deposited at 0.3 mm/rev to ensure the quality was not lost over increased length and to evaluate distortion.
 Visual Assessment Rating 10/10	RUN 39 Long run of weld as RUN 38

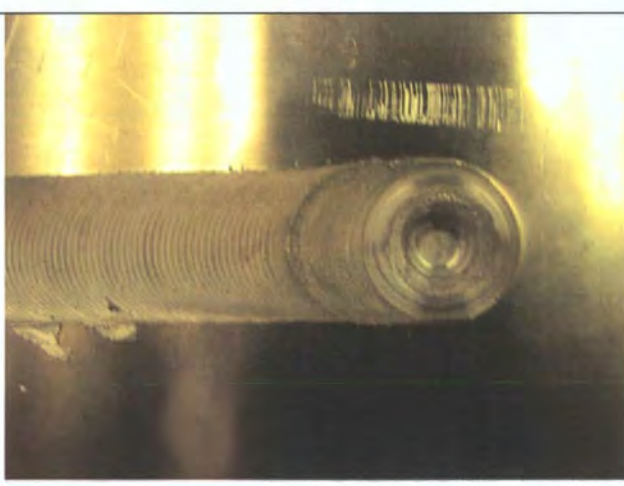
<table>
<tr><td>
Visual Assessment Rating 10/10</td><td>RUN 40
Re-introduced 0.5mm centreline offset towards extrusion
Long run of weld at settings as RUN 38</td></tr>
<tr><td>
Visual Assessment Rating 10/10</td><td>RUN 41
Additional 0.25 mm offset towards extrusion, giving 0,75mm total.
Good Weld</td></tr>
</table>

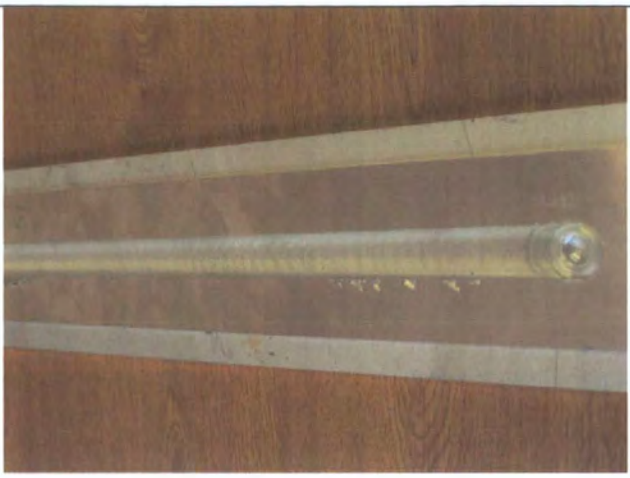
Appendix 4 Results of TRIAL 4

 Visual Assessment Rating 2/10	RUN 42A Did not weld properly as tool force opened up the clamping slightly and weld observed as not exactly on centreline.
 Visual Assessment Rating 9/10	RUN 42B Increased clamping force. Moved weld 0.25mm onto centreline. Improved weld, still opened slightly at start during insertion tool forces, but closed as weld progressed.
 Visual Assessment Rating 8/10	RUN 42C Still on centreline, weld improved after first 15mm initiation. Weld 100mm long, good condition. All runs were recorded under RUN 42 as weld parameters were not changed, only clamping and position.

Appendix 5 Results of TRIAL 5

 Visual Assessment Rating 7/10	RUN 50A A short trial run was performed which gave good visual appearance with the exception of the start which lost integrity under the penetrative welding loads.
 Visual Assessment Rating 4/10	RUN 50B View of Start A longer weld was produced. The start was poor with clamping being insufficient to retain fully the upper plate under the penetrative welding forces.
 Visual Assessment Rating 9/10	RUN 50B View of End Same weld as above showing End Detail. Once established, the weld visual quality was excellent.

 Visual Assessment Rating 9/10	RUN 50B Showing the full length weld.
 Visual Assessment Rating 9/10	RUN 51 View of Start Settings as RUN 51, but clamping improved with angled clamps to help restrain lateral movement of top plate. The start was an improvement over RUN 50 with a good weld, but more development of clamping of the top plate or dwell required to optimise further.
 Visual Assessment Rating 9/10	RUN 51 View of End Focus on end condition shows the weld condition was good once established.

<table>
<tr><td>
Visual Assessment Rating 9/10</td><td>RUN 51
A view of the full weld length shows good uniformity.</td></tr>
</table>