PROJECT TITLE: Crashworthiness of Joints in Aluminium Rail Vehicles. ALJOIN

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ISSUED BY: D’Appolonia

CIRCULATION: All Consortium members
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1 PROBLEM AddressED

Aluminium alloys are now in widespread use in Europe and elsewhere for rail vehicle construction from commuter to express trains. In recent years there has been an increased effort to investigate and improve the crashworthiness of passenger rail vehicles to minimize fatalities and injuries if an accident does occur.

The strength, integrity and performance of aluminium welds in rail vehicles contribute greatly to the overall body shell strength and crashworthiness. To ensure passenger compartment structural integrity, load carrying welded joints must not fail before the compartment structure as a whole can deform in a ductile manner to reduce the risk of crash impact to a tolerable level.

The phenomena of weld unzipping has been evident at many recent rail incidents. In recent collisions involving seam welded aluminium rail coaches, some of the longitudinal seam welds fractured for some meters beyond the zone of severe damage, the panels themselves generally being intact without significant distortion.

Figure 1 - Example of an unzipped weld

Fusion welded joints of cold worked and heat treated aluminium alloys suffer from a loss of strength in the over aged zones due to welding thermal cycles. Within the over aged zones, the strength minimum is usually found at the interface between the heat affected zone (HAZ) and the parent material and at the fusion line. The strength reduced zones have profound effects on plastic deformation capability and fracture resistance of welded joints of aluminium alloys. The designer needs the data to assess this fracture phenomenon and be able to take appropriate measures to avoid it properly, taking into account the local material weakness in the Heat Affected Zone (HAZ) of the weld and the severe loading conditions.

The experts on crashworthiness\(^1\) agree (in Cullen recommendation 57) that consideration should be given, in the case of new vehicles constructed of aluminium, to the following:

- use of alternatives to fusion welding;

\(^1\) Part 1 – “The Ladbroke Grove Railway Enquiry”, Health and Safety Executive, UK
o use of improved grades of aluminium less susceptible to fusion weld weakening;
o further development of analytical techniques to increase confidence in the crashworthiness of rail vehicle structures, particularly those constructed of aluminium.

In this context, the ALJOIN project should contribute significantly to the European policies in terms of railway safety.

The strategy that ALJOIN will use to approach the problem can be described as follows:

o creation of performance criteria for the properties of aluminium welds in the new generation of rail vehicles in terms of their stress/strain performance;
o assessing the existing methods of joining techniques and joints;
o static and dynamic modelling of joints and structures;
o formulating new joining techniques and joints;
o definition of a method for assessing crashworthiness;
o demonstration and validation of the innovative technologies developed against the performance criteria.

2 EXPECTED IMPACT

Real improvements in the safety of rail vehicles, introduction of innovative techniques for aluminium welding and improvements in the crashworthiness of the new generation of rail vehicles are among the main ALJOIN outputs.

The expected impact is a real improvement in the safety of the new generations of rail vehicles, contributing to the safety of European citizens as well as to the EC policies in safety issues and standardisation of the materials and aluminium welding methods used in the rail industry.
3 PROJECT SUMMARY

ALJOIN is planned to last three years. The first year will be dedicated to the research phase and will focus on the creation of a performance criterion to assess the aluminium welding in the new generation of rail vehicles, as well as the existing joints and joining techniques.

The second and third years will concentrate on the formulation of innovative joining techniques, static and dynamic modelling of joints and structures, development of an assessment method for crashworthiness, demonstration and validation.

The ALJOIN project will address the many existing fusion-welding methods and the strength and weakness of emerging alternatives (e.g. Friction Stir Welding, AC Pulsed MIG Welding, Laser Techniques, Hybrid Laser/arc techniques, etc.).

The ALJOIN project will also appraise the use of alternative non-fusion welding techniques, such as friction stir welding (FSW), using improved grades of aluminium less susceptible to fusion weakening.

Performance criteria for aluminium welds in the new generation of rail vehicles and a method for assessing their crashworthiness will be defined.

The project work-flow is shown in Figure 2.

The work programme is then briefly presented with reference to the main activities.
Figure 2: Project Work-Flow

**WP 2: Performance Criteria**

**Objectives:**

- To determine the performance specifications required by critical aluminium joints in rail vehicle cars to ensure the structural integrity.

**Description:**

The future of aluminium rail vehicles will depend on the performance of aluminium joints. This Work Package will assess the performance requirements for aluminium joints to ensure the structural integrity and the crashworthiness of the vehicles.
### WP 3: Existing Joint Assessment

#### Objectives:

- To provide physical evidence of the energy absorption capability of aluminium alloy welds by testing;
- To define failure criteria suitable for aluminium alloy welds;
- To investigate performance and failure criteria for aluminium bolted joints;
- To explain test results assessing the adequacy or inadequacy of current design and construction practices of aluminium alloy welds in the context of crashworthiness.

#### Description:

The properties of the various constituents of the weld will be investigated to understand joint performances. A systematic appraisal of structural performance of aluminium welds in body-shells of rail vehicles made by currently accepted design and construction practices will lead to the acquisition of more knowledge of how welded aluminium joints behave under static and crash loading conditions, with particular respect to energy absorption capabilities.

The research work carried out within this Work Package will comprise the following activities:

- Material characterisation
- Joint strength tests. Samples of welded joints of aluminium alloy extrusions will be manufactured using the same alloys and welding procedures as those used for construction of rail vehicles or will be obtained directly from body-shells of existing rail vehicles.
- Analyses of test results by finite element method, fracture mechanics principles and material properties.
WP 4A: Static Modelling of Joints

Objectives:

- Development, implementation and validation of material failure models for welds of aluminium alloys;
- Definition of the main material and structural parameters affecting the mechanical behaviour of the joints;
- Numerical modelling of joints in rail vehicle body shell subjected to complex stress system including welding residual stresses.

Description:

The constitutive behaviour is strictly related to the failure mechanisms of the welded material. Usually failure occurs due to fatigue crack propagation that grows from points characterised by lack of penetration or welding defects.

![Example of defects between final run and parent metal](image)

Failure mechanisms will be investigated by metallurgical and micro-structural examinations.

Potential failure criteria will be proposed for implementation and validation. Validation of material failure models will be carried out by an iterative process in which the finite element model will be updated using test results to reproduce deformation and failure behaviours emerged from testing.

The mechanical behaviour of the joints will be evaluated, also considering welding defects such as flaws, residual stresses and macro-/micro-structural changes. The prediction of the fracture mechanism occurring in the welded regions will be used to evaluate the progressive failure of the entire component.

The constitutive model will be basically a plastic model that will take into account the complex interactions between various stress components and the coexistence of various failure modes.

A crashworthiness concept will be developed in the model in order to consider the progressive failure mode of the entire welded component. The possible constitutive model will be tuned using experimental data.
WP 4B: Dynamic Modelling Components and Structures

**Objectives:**

- Design and modelling of crashworthy structures which deform under a controlled load and preserve sufficient survival space around the occupants to limit bodily injury during an accident.
- Numerical analysis of components and structures subjected to quasi-static and impact (dynamic) loading conditions in order to evaluate the structural response in terms of mean axial crushing force, total energy absorption, load efficiency and uniformity, deformation mechanism.
- Critical comparison of the numerical simulations with the experimental results on small- and full-scale samples.
- Review of load conditions, rates of strain and modes of deformation of aluminium alloy welds of the rail vehicle under crash and derailment scenarios.

**Description:**

Thin-walled columns are basic components in the concept and design of the body structures of land vehicles, and their crashworthiness behaviour is of fundamental importance in the safety design of the whole vehicle because their plastic collapse is the mechanism that is used to dissipate the kinetic energy of the vehicle in an accident.

![Crushing simulation of sandwich stiffened members](image)

The results on structures that do not consider the joints’ characteristics will be used as a starting point to understand the effects of the joint characteristics on the structural response. Modelled structures will comprise thin-walled members and sandwich members with various types of cross sections in which the influence of the welding effect is studied. The energy dissipation of the joint failure will be evaluated within a simple model in order to rank the crashworthiness of the various welded joints with reference to the base material and the welding process. The dissipated energy will be evaluated versus displacement and crushing force response. The modelling work will reflect the performance criteria defined in WP 2.
WP 5: New Joining Techniques and Joints

Objectives:

- Investigation of alternative welding techniques and joint design to improve joint strength;
- Comparison of Friction Stir Welding with traditional methods.

Description:

To improve the safety of aluminium rail vehicles, the present work will investigate new joint design and welding techniques.

New Joint Design

One issue is the partial penetration design of the welded joints in some of the rail vehicles: the present work will assess and redesign the partial penetration joints if necessary.

Having understood the structural behaviour of aluminium alloy welds and the methods for assessing them, alternative joint designs for fusion welding will be proposed and investigated.

Finite element analysis will be employed to systematically investigate various options. Optimal joint designs will be identified, also considering the practical and economic implications of using the new design.

New welding techniques

Friction stir welding (FSW) of aluminium alloys has emerged as an attractive alternative to traditional welding because it is a non-fusion process. Mechanical properties and joint tests of friction stir welds, in many instances, indicated their superiority over fusion welds.

Because of the rapid expansion of its application, systematic investigations are required into the strength, ductility and fracture behaviour. The behaviour needs to be assessed and understood so that designers can have confidence in their designs.

In addition to FSW, other welding techniques such as AC pulsed MIG, laser welding and hybrid laser/arc welding will be reviewed and carefully considered.
**WP 6: Exploitation Products and Standards**

**Objectives:**

- The commercial exploitation of the new technologies developed to improve the crashworthiness of aluminium alloy vehicles and the identification of possible improvements to rail vehicle standards.

**Description:**

It is envisaged that new joining technologies and materials will be used for further development and, eventually, commercial exploitation in rail vehicle construction. Additionally, exploitation will be undertaken to develop other solutions in other transport sectors and in different industries.

The results of ALJOIN will be disseminated to the CEN representatives so that the dynamic performance of vehicle joints can be considered to update CEN codes of practice and standards. This will compliment the very important activities related to the inclusion of dynamic requirements in crashworthiness standards for rail vehicles. Criteria for the exploitation of the results in relation to passive safety standards and Eurocodes will be developed as well.

**WP 7: Method for Assessing Crashworthiness**

**Objectives:**

- To determine the most appropriate tests to demonstrate the crashworthiness of the rail vehicles’ demonstrators.

**Description:**

Small and large scale testing will be developed to assess the deformation characteristics of aluminium welded joints and substructures. In addition to those facilities to be used in WP3, the work in WP7 will use the structural features test laboratory which includes a 7 m · 4 m strong floor and 4 m · 4 m reaction wall capable of withstanding loads of up to 5 MN. This is equipped with a range of servo-controlled hydraulic actuators, up to 5 MN capability, and a modular system of beams and columns to create a versatile environment for high quality structural testing. Critical features of the rail vehicle demonstrators will be installed on the strong floor and wall, and hydraulic actuators will be used to load, in a quasi-static fashion, the structure in a realistic manner. The deformation behaviour and the energy absorbing capacity will be monitored and recorded. The behaviour recorded in these tests will be compared with the numerical modelling in WP4b and used to optimise the testing approach for the full scale impact.
### WP 8: Demonstrators

**Objectives:**

- To apply the developed methods to the assessment of crashworthiness of large-scale components;
- To demonstrate the structural performance of welded joints in aluminium alloys obtained by means of innovative techniques and design.

**Description:**

**Large-scale demonstration tests of components and assessment.**

Large-scale tests of components of body shells will be performed under controlled laboratory loading conditions which will reflect those in vehicle collision scenarios. In parallel to the tests, the developed assessment methods will be used to predict the structural behaviour of the large-scale components. The predictions will be compared to the results of the tests.

**Demonstration of structural performance of welded joints by new welding technique and design.**

Structural components will be made and tested to demonstrate improvement of welded joints made by new welding techniques and design. These tests will also allow the effectiveness of the developed methodology for assessing crashworthiness (WP7) to be quantified.

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### WP 9: Validation

**Objectives:**

- Implementation of method defined in Work Package 7.
- Full Impact Testing.
- Quasi Static Testing.
- Using methods determined in WP7 the validation work package will aim to show how the practical development meets the criteria set out in WP2.

**Description:**

The validation activity will include validation by testing and validation of modelling. WP9 will investigate the demonstration models using the techniques and methods devised in WP7. Specific areas to be investigated will be weld integrity, energy absorption through the performance of crumple zones and passenger shell integrity. This will be analysed with respect to the performance criteria established in WP2.

Project GANTT chart is reported in Annex 1.
4 A STRONG PARTNERSHIP

The ALJOIN consortium brings together a partnership consisting of D'Appolonia (contract research organisation), ARRC (railway research), Bombardier Transportation (railway vehicles manufacturing), Alcan (material and equipment), DanStir (welding technology), and TWI (welding research), to successfully address the ALJOIN objectives.

D’APPOLONIA

D’Appolonia is an engineering company involved in research, consultancy and technology transfer activities with a staff of 120 engineers having advanced technological background and experience.

The Applied Research Area, belonging to the industry division of D’Appolonia, and having notable experience in the analysis and design of complex structures, will be directly involved in the ALJOIN project (e.g. dynamic modelling and design of crashworthy structures).

BOMBARDIER

Bombardier Transportation is currently the global leader in the rail equipment, manufacturing and servicing industry. Indeed, the acquisition of Adtranz vaulted Bombardier Transportation into the leadership position in the global rail transportation market. This acquisition complemented Bombardier’s transportation activities in terms of geographical markets, products and services, broader capabilities, expertise and assets. Its wide range of products includes passenger rail vehicles and complete rail transportation systems, as well as manufacturing of locomotives, freight cars, propulsion and controls and providion of signalling equipment and systems.

ARRC

The Advanced Railway Research Centre (ARRC) was set up as a joint venture between the British Railways Board and the University of Sheffield to act as a link between academia and the rail industry.

ARRC’s mission is to develop and maintain the highest standards of excellence in rail-related research of international standing. The core expertise of ARRC is based on four research teams:

- Rail vehicle safety.
- Rail vehicle materials, design and production.
- Rail freight and intermodality.
- Urban freight logistics.
DanStir is a new company established in August 2000 with a background in material research. DanStir is a full Industrial Member of "The Welding Institute, TWI", in Cambridge, UK and is mainly an established friction stir welding site offering services to industries worldwide.

The inspiration to form DanStir originated from activities at the Risø National Laboratory in Denmark, where friction stir welding was introduced to the Materials Research Department by British Aerospace, UK.

The Managing Director of DanStir has extensive experience in international collaboration on materials research and in friction stir welding. The technical staff has extensive experience in numerically operated machinery and specifically in friction stir welding.

TWI is one of the world's foremost independent research and technology organisations and provides industry with technical support in welding and associated technologies through: information, advice and technology transfer, consultancy and project support, contract R&D, training and qualifications, personal membership.

Know-how within TWI covers not only joining and fabrication technologies, but also structural analysis, fracture and design.

The Finite Element Analysis Section of The Welding Institute will be active in ALJOIN.

Alcan is a multinational, market-driven company and a global leader in aluminium and specialty packaging.

Research and technology within Alcan comprise a global system of research laboratories, applied engineering centres and plant technical departments. The research laboratories play a major role in innovation through basic and applied research. Alcan’s R & D efforts are focused on core processes and products, assisting operating units to achieve increased productivity, higher quality and reduced costs. In addition, the R & D centres are responsible for creating value-added options for Alcan through the development of new products and processes. Know-how within Alcan covers advice on construction with appropriate joining techniques, selection of the type of joint and manufacture, and expertise in welding aluminium, using all of the current techniques.
| TASK Number and Name          | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 | 31 | 32 | 33 | 34 | 35 | 36 |
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| WP 1: Project Management   |   |   |   |   |   |   |   |   |   |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| and Dissemination          |   |   |   |   |   |   |   |   |   |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| WP 2: Performance Criteria |   |   |   |   |   |   |   |   |   |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| WP 3: Existing Joint       |   |   |   |   |   |   |   |   |   |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Assessment                 |   |   |   |   |   |   |   |   |   |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| WP 4A: Static Modeling     |   |   |   |   |   |   |   |   |   |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| of Joints                  |   |   |   |   |   |   |   |   |   |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| WP 4B: Dynamic Modeling    |   |   |   |   |   |   |   |   |   |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Components and Structures  |   |   |   |   |   |   |   |   |   |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| WP 5: New Joining Techniques and Joints |   |   |   |   |   |   |   |   |   |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| WP 6: Exploitation Products and Standards |   |   |   |   |   |   |   |   |   |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| WP 7: Method for Assessing Crashworthiness |   |   |   |   |   |   |   |   |   |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| WP 8: Demonstrators       |   |   |   |   |   |   |   |   |   |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| WP 9: Validation          |   |   |   |   |   |   |   |   |   |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |

Meetings

- Kick-off Meeting
- Mid-term Meeting
- Final Meeting