Crashworthiness of Joints in Aluminium Rail Vehicles

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Abstract

Research into the crashworthiness of joints in aluminium rail vehicles has been intensified since the rail accident at Ladbroke Grove. This paper addresses the issues of weld unzipping and looks at alternatives to fusion welding. Existing joints have been characterised to determine the effects of the weld filler material, the type of aluminium and the heat affected zone.

Work is continuing to investigate:
- Alternatives to fusion welding;
- Improved grades of aluminium;
- Analytical techniques to model the static and dynamic behaviour of aluminium joints.
Introduction

Aluminium alloys are in extensive use for rail vehicle manufacture in Europe, from metros through commuter to express trains. Aluminium car bodies are manufactured from longitudinal extrusions that are usually joined by fusion welding. Following recent accidents involving rail vehicles manufactured from aluminium where the longitudinal joints have failed in an unpredictable manner have highlighted the need to understand and improve the crashworthiness of these critical joints.

The strength, structural integrity and performance of joints in aluminium rail vehicles naturally contribute greatly to the overall body shell strength and crashworthiness, as the maintenance of survival space is a primary objective of a crashworthy design. It is essential to ensure the passenger compartment structurally integral joints must not fail before the structure as a whole can deform in a predictable manner and the energy absorption devices can operate effectively.

In the UK, following the Ladbroke Grove rail accident in October 1999 (Fig. 1), where an aluminium rail vehicle was involved in a near head-on collision with a high speed train, a number of joints failed in a catastrophic manner from a phenomena know as "weld unzipping". A public inquiry was carried out after the Ladbroke Grove accident and in the subsequent report, The Right Honourable Lord Cullen QC, stated ‘the aluminium extrusions had fractured along the weld lines and that there was a lack of plastic deformation’ and that ‘the structure appeared to have failed along the welds rather than deforming in a controlled manner’ [1].

![Fig. 1: The Ladbroke Grove Rail Accident](image)

This resulted in the experts on crashworthiness agreeing that consideration should be given, particularly in the case of new vehicles constructed of aluminium, to the following:

- The use of alternatives to fusion welding;
- The use of improved grades of aluminium which are less susceptible to fusion weld weakening;
- The further development of analytical techniques to increase confidence in crashworthiness of rail vehicle structures, particularly those constructed of aluminium.

The Rt Hon Lord Cullen endorsed this research need and it became *Recommendation 57* in the Ladbroke Grove Inquiry.
ALJOIN

From Recommendation 57, a cooperative coordinated European project called Crashworthiness of Joints in Aluminium Rail Vehicles (ALJOIN). The project has a strong competent partnership consisting of 6 participating companies and research centres from 5 European countries, these are;

- Alcan (Switzerland), is a multinational company and a global leader in aluminium production;
- NewRail is based at the University of Newcastle and undertakes rail related research to the highest international levels;
- Bombardier Transportation (Sweden), is a global leader in the rail equipment, manufacturing and servicing industry;
- DanStir (Denmark), recently established as a friction stir welding site offering services to industries world wide;
- D’Appolonia (Italy), is a specialist engineering company involved in research, consultancy and technology transfer activities;
- TWI (UK), is one of the world’s foremost independent research and technology organisations and provides industry with technical support in welding and associated technologies.
- Railway Safety and Standards Board, RSSB were invited to contribute as an associate partner to the ALJOIN project during the first year

ALJOIN has a duration of three years, and the aim of the project is;

“To provide sufficient knowledge to design cost effective aluminium rail vehicle bodies that will not fail by catastrophic joint failure under extreme loading”

In this first year ALJOIN was dedicated to the research phase to thoroughly investigate existing joints and joining techniques. In addition the rail specific effort will focus on the creation of a performance criterion to assess aluminium welding in the new generation of rail vehicles

Subsequent years will focus 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.

ALJOIN will consider the many existing fusion welding methods and the strength and weaknesses of emerging alternatives. The project will also appraise the use of alternative non-fusion welding techniques particularly friction stir welding (FSW) and the use of improved grades of aluminium potentially less susceptible to fusion weakening. Fusion weakening is caused by the high temperatures generated by the fusion welding process that changes the material properties of the parent metal in the vicinity of the weld, the affected area is known as the heat affected zone (HAZ). The width of the HAZ can vary greatly and is dependant of a variety of factors, among them being the thickness of weld, the geometry of the extrusion (in the case of longitudinal railway vehicles), along with numerous welding parameters.
Current Work

The ALJOIN project has been running for over a year and the progress so far has been the completion of the performance criterion and the investigation into the existing joints. A thorough testing exercise has been carried out on the commonly used 6005A T6 aluminium alloy using butt welds with both 4000 series silicon alloy and 5000 series magnesium alloy weld fillers. Numerous different tests, both static and dynamic, have been performed to attempt to categorise the material properties for the parent metal, the HAZ and the weld itself.

Stable and Unstable Fracture

To understand weld unzipping, fracture mechanics approaches are being used. The failure along the weld lines observed in the Ladbroke Grove Rail accident was not a new phenomenon, and it can be quantified by observing the difference between stable and unstable fracture.

When a structure is subjected to certain load types the propagation of a crack is driven by the stress field that develops ahead of the crack tip. In fracture mechanics terms, the stress and strain fields can be characterised by a single parameter such as the stress intensity factor, \( K_I \), under elastic conditions or the J-integral \( J_I \) or crack opening displacement under conditions of significant plasticity. Such parameters describe the mechanics of the crack in terms that include the applied load and the length of crack.

The resistance of a particular material to fracture is the fracture toughness. This is commonly described by a single value of \( K_I \), or \( J_I \), at which fracture occurs in that material. However, in thin sections of tough metals, fracture is not a sudden event, but is a process of deforming and tearing material ahead of the crack tip. This can be characterised by a tearing resistance curve, which plots the crack growth resistance \( R \) in a material against \( K_I \), or \( J_I \), known as a K-R or J-R curve, which captures the relationship between the crack tip stress and strain fields and the process of fracture for a particular metal.

The balance between no fracture, stable fracture and unstable fracture is governed by the relative magnitudes of the stresses and strains ahead of the crack tip and the ability of the material to resist those stresses and strains. This can be represented by a comparison of the stress intensity factor, or J-integral, for the cracked and loaded structure and the tearing resistance curve for the metal under consideration.

No fracture occurs if the applied \( K_I \), or \( J_I \), is less than the \( K_{\text{material}} \), or \( J_{\text{material}} \), then the crack will not extend. Unstable fracture occurs when the applied \( K_I \), or \( J_I \), is greater than the \( K_{\text{material}} \), or \( J_{\text{material}} \), and the crack will extend. Stable fracture is when the applied \( K_I \), or \( J_I \), is initially greater than the \( K_{\text{material}} \), or \( J_{\text{material}} \), and becomes less than the \( K_{\text{material}} \), or \( J_{\text{material}} \), as the crack extends then the crack will arrest. It will not extend until the applied \( K_I \), or \( J_I \), is increased sufficiently for the material resistance to fracture to be overcome again.
This is illustrated below (Fig. 2) for a material with a known tearing resistance in the form of a J-R curve and a structure with a known crack tip stress and strain field in the form of a relationship between applied $J_l$ and crack length.

![J-R curve diagram]

**Fig. 2: Stable and Unstable Fracture**

In the stable fracture diagram it can be seen that a crack will grow to a length $a+\Delta a$ then the material resistance will become greater than the applied $J_l$ and the fracture will arrest.

From the unstable fracture diagram it can be seen that the applied $J_l$ does not intercept the material resistance curve but is tangential to it. This is where crack growth is unstable and the crack does not arrest.

The use of crack tip opening angle (CTOA) testing for the prediction of ductile fracture in the three zones; parent metal, HAZ and the weld itself are being researched by NewRail. The technique involves removing tearing samples directly from representative welded aluminium double skinned extrusions. The specimens are pre-notched in the zone under investigation and a tensile load is applied to cause tearing (Fig 3). The loading of the specimen is carried out in displacement control, load and displacement data are recorded along with video footage. Using images captured form the video it is possible to determine the CTOA (Fig 4).

![Tearing Test set-up and Captured Tearing Image]
Future Work

To address the points raised in Recommendation 57 of the Ladbroke Grove Inquiry, the next phases of the ALJOIN project will investigate the following:

- the use of alternatives to fusion welding

One alternative to fusion welding is friction stir welding (Fig. 5), which is a non-fusion welding process, and was invented and patented in 1991 by TWI in Cambridge, United Kingdom and is a joining technique that operates below the melting point of the work pieces. Hitachi in Japan have already used FSW to join the longitudinal joints of their aluminium commuter and express railway vehicles (Fig. 6) and there is interest in Europe for the use of FSW in the manufacture of aluminium rail vehicles [2]

Fig. 5 Friction Stir Welding    Fig. 6: Hitachi Express Train
Principle and Microstructure   Photograph courtesy of Hitachi
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- The use of improved grades of aluminium which are less susceptible to fusion weld weakening

Alcan have been investigating material developments to address this issue and have produced two alloys which have a refined grain structure and improved ductility and hence crashworthiness. For the full length carbody extrusions the aluminium alloy that has commonly been used is 6005A but with the improvements of the new alloys, these are now suitable for full length extrusions. Further research is also being carried out to investigate the difference between different heat treatments. Most 6000 series alloys are used in naturally aged T6 condition where the mechanical strengths are at the maximum level but the ductility is poor. An alternative to this is the over-aged T7 condition which normally has poor strength, but work is being undertaken to enable the T7 condition to have similar strengths to that of T6 but with improved ductility.

- The further development of analytical techniques to increase confidence in crashworthiness of rail vehicle structures, particularly those constructed of aluminium.

The data from the completed existing joint testing will be used in two ways, firstly as a benchmark for the future work carried out in ALJOIN, when the
new joining techniques are investigated and new materials are considered. Secondly, the data will also be used for modelling purposes to tune finite element analysis models to address the third point raised in Recommendation 57 of the Ladbroke Grove enquiry.

This research will culminate in demonstrations and validation of the technologies developed

Conclusions

ALJOIN is addressing all the issues laid out by Rt Hon Lord Cullen in Recommendation 57 of the Ladbroke Grove inquiry.

Current work carried out in the project enables to consortium to move into the next phase, which is to establish damage parameters for finite element analysis models. Using the static and dynamic results from the testing programme for fusion welding, it will be possible to ascertain a methodical approach for determining the damage parameters. Once confidence is established in the procedure, it will be possible to move ahead with the future work of investigating alternatives to fusion welding and the use of improved grades of aluminium which are less susceptible to fusion weld weakening.

The findings of the ALJOIN project aim to produce real improvements in the safety of rail vehicles and improvements in the crashworthiness of the new generation of rail vehicles. The expected impact is a real improvement in the safety of the new generation of aluminium rail vehicles, contributing to the safety of European citizens as well as to the European Commissions policies in safety issues.

References:


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