Dynamic behaviour of AA 2024 under blast loading : experiments and simulations

11th International Aluminium Conference - 'INALCO' 2010
'New Frontiers in Light Metals'
Laurens Katgerman and Frans Soetens (Eds.)
IOS Press

Dynamic Behaviour of AA2024 under blast loading: Experiments and Simulations

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Abstract - The dynamic behaviour of AA2024-T3 is investigated. Dynamic tensile tests using a servo-hydraulic and a light weight shock testing machine (LSM) have been performed. The servo-hydraulic test machine proves to be more reliable and reaches higher strain rates. Neither test revealed any strain rate effect of AA2024-T3. Two types of fracture tests were carried out to determine the dynamic crack propagation behaviour of this alloy, using prestressed plates and pressurized barrels, both with the help of explosives. The prestressed plates proved to be not suitable, whereas the barrel tests were quite reliable, allowing to measure the crack speeds. Computer simulations with a user defined, rate dependent cohesive zone model were in agreement with experiments, capturing the rate toughening effect.

1. Introduction

Aluminium is the airplane building material for excellence for many reasons: light weight, good mechanical properties, good fatigue behaviour, relatively low price, adequate workability, huge engineering experience, etc. This will remain so in the decades to come, in spite of the growing importance of composites and hybrid materials. 2024T3 aluminium is one of the best known high strength aluminium alloys and widely used as aircraft aluminium.

Triggered by the growing terrorist threat, the EU VULCAN project [1] aims at strengthening airborne structures under blast and fire. An explosion is a highly dynamic event and the fuselage material behaves in a different manner as under a static load. Stress waves, inertia, temperature and strain rate effects take place. Although the strength and fracture behaviour of airplane aluminium alloys (e.g. AA2024) under quasi-static/fatigue loading is well known, its dynamic behaviour is less well understood. Within the VULCAN project, the strain rate sensitivity and the dynamic fracture behaviour of AA2024-T3 has been investigated.

This mechanical data is necessary in order to validate and develop new finite element models. Dynamic crack propagation experiments and simulations using a user defined rate dependent cohesive zone model are compared.

2. Dynamic tensile tests

High strain rate tests have been performed using two different test machines:

- A servo-hydraulic high-speed single shot test machine.
- A so-called lightweight shock testing machine (LSM).

The servo-hydraulic test machine was used in [2] to measure the dynamic properties of S2 glass fibres, Glare-3 and AA2024-T3. Stresses are directly computed from the measured force, and the strain and strain rates are obtained from digital processing of high speed camera images. The LSM, on the other hand, is normally used for verifying equipment's resistance to underwater shock induced deck motions on board of naval ships. Stresses are computed from the mass and the acceleration of the clump mass and strains are measured by means of strain gauges. The servo-hydraulic setup is preferred to the LSM, since it allows reaching higher strain rates, up to 200 1/s, an order of magnitude higher than the LSM. Also the results are more reliable, with less dynamic oscillations. On the other hand, the LSM allows for testing substantially larger specimens, for example structural details, at dynamic loading rates [3]. Figure 1 shows the two setups.

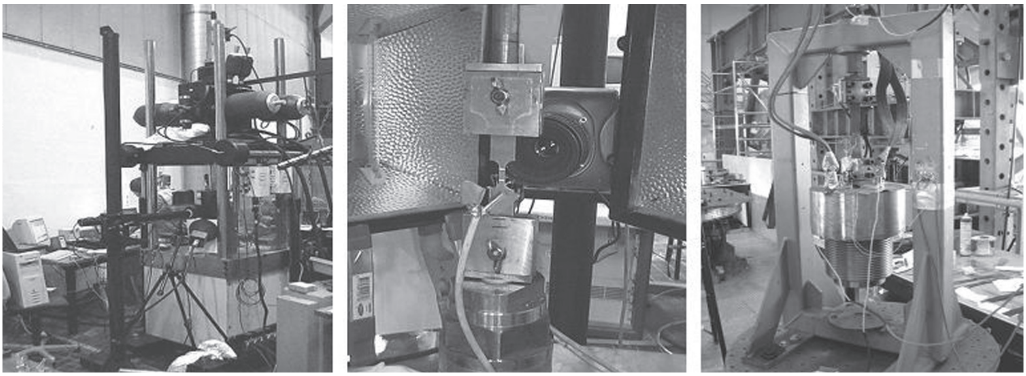

Figure 1: (left) servo-hydraulic high-speed machine setup; (middle) sample and high speed camera; (right) LSM setup.

The specimens tested with the servo-hydraulic machine are 3 mm wide and 1 mm thick. Strain rates up 200 1/s are attained. No sign of strain rate dependency was observed, see Figure 2. The average failure strain rate was ef=0.2 and the failure strength sf= 550 MPa, irrespectively of the strain rate.

The specimens tested with the LSM were 40 mm wide and 1.0 mm thick. The average strain rate was 30 1/s. The interpretation of the results is not straightforward, since the measurement reflected dynamic structural effects (not shown). The dynamic LSM tests showed an average failure strain ef=0.18 and the average failure strength sf= 407 MPa. Figure 3 shows that failure occurs along the maximum shear direction, at 45^{o} from the loading direction. Hollow specimens, with a hole diameter of 5 mm, were also tested to show the effect of high stress triaxialities on reducing the failure strain. This was indeed confirmed by experiments, which showed a lower failure strength and strain sf=279 MPa and ef=0.017 respectively. The hollow specimens failed in the normal to the loading direction.

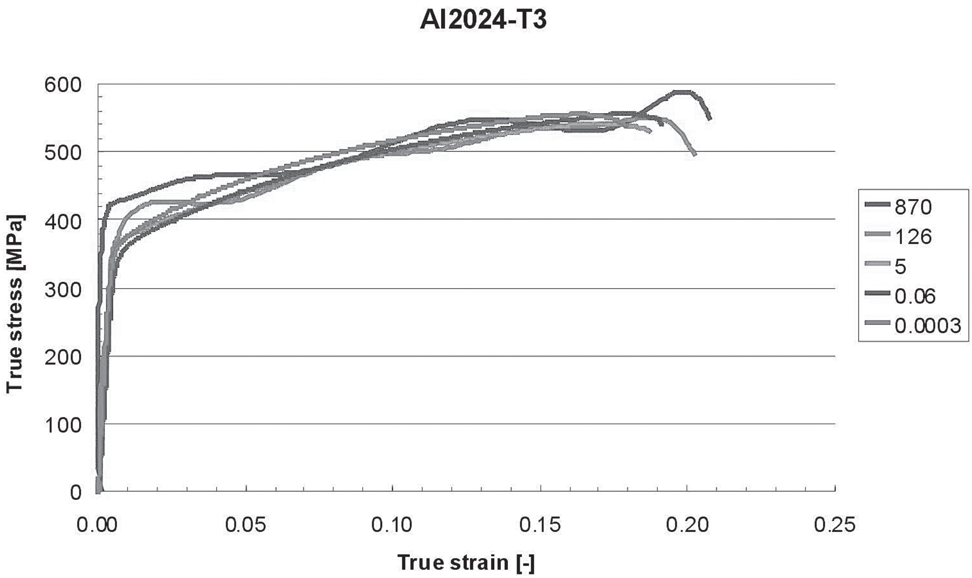

Figure 2: Stress-strain curves at different strain rates, with servo-hydraulic high-speed machine.

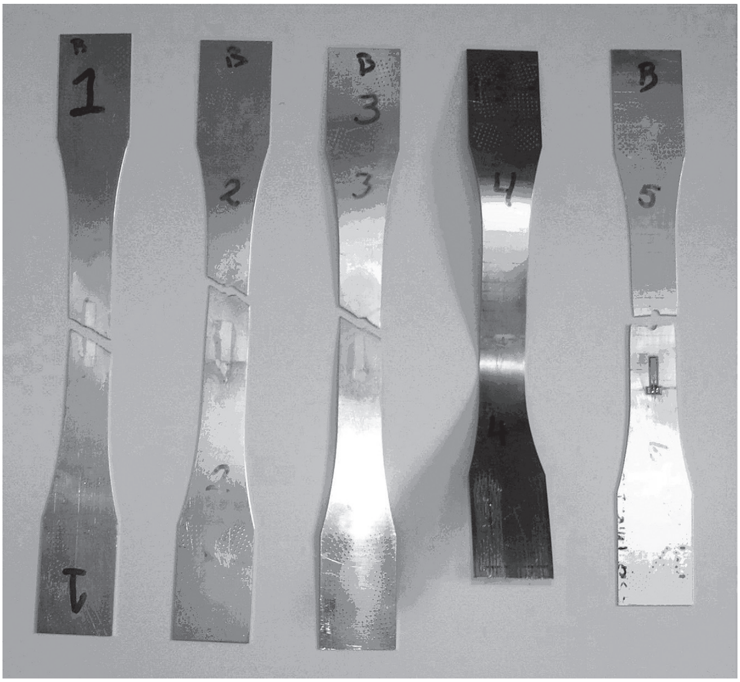

Figure 3: Aluminium specimens after failure, using LSM machine.

3. Dynamic fracture tests

Two types of fracture experiments have been performed:

3.1 Prestressed plate tests.

Flat plates of dimensions 800-1600 mm (w-l) were prestressed at different stress levels, 100 and 200 N/mm2. Crack propagation was triggered by creating a notch (200 mm long) in the middle of the plate, by means of an explosive charge. Crack propagation was recorded using high speed camera recordings, which allowed computing the crack speed. Figure 4 shows the hydraulic used in the prestressed plate tests and the explosive charge used to create the prenotch.

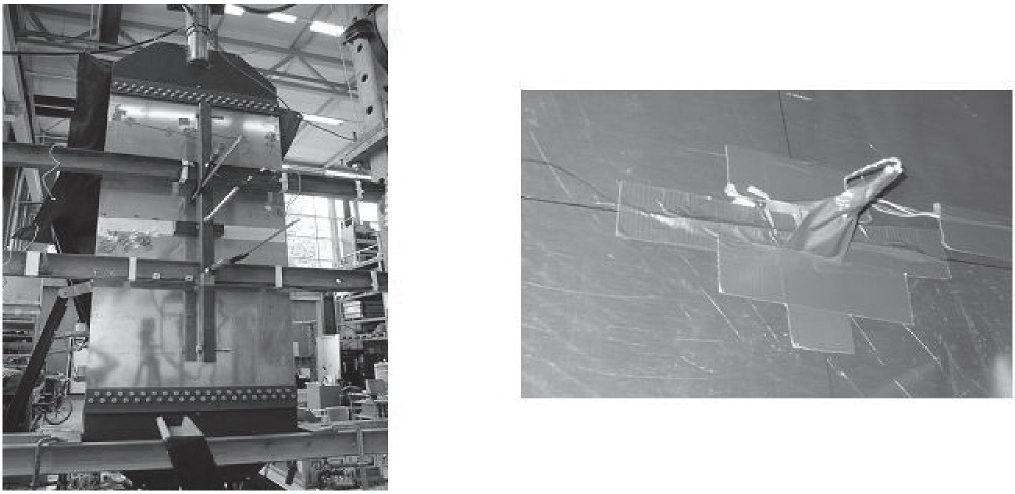

Figure 4: (left) prestressed plate setup; (right) line explosive charge to create prenotch.

It turned out that this setup was not suitable for studying crack propagation for a number of reasons: unknown extent of the damage near the explosive charge, out of plane movement of the plates due to the explosive load; asymmetric crack propagation. Figure 5 shows a sequence of snapshots during crack propagation. Fracture occurred perpendicular to the loading direction (mode-I).

3.2 Pressurized barrel tests.

In the barrel tests, a barrel with a prenotch (56 mm long) is pressurized, and crack propagation is triggered by the explosion of a TNT charge placed inside, in the middle of the barrel. The barrel dimensions are: 1.2 m by 1 m (diameter x height), a scaled down simple model of a fuselage. The top and bottom of the barrel are made of massive steel plates, which are firmly fixed relative to one another in the vertical direction. The skin of the barrel is fixed to the end plates with bolts. The explosive charge is spherical and has a mass of 54 gr. To simulate flying conditions, the barrel was pressurized at 200 kPa. The prenotch is taped off to avoid depressurization. Upon pressurization, the explosive is detonated, triggering crack propagation. Figure 6 shows a sketch of the barrel test setup, the high speed cameras and the measured blast pressure inside the barrel.

Figure 5: Crack propagation snapshots.

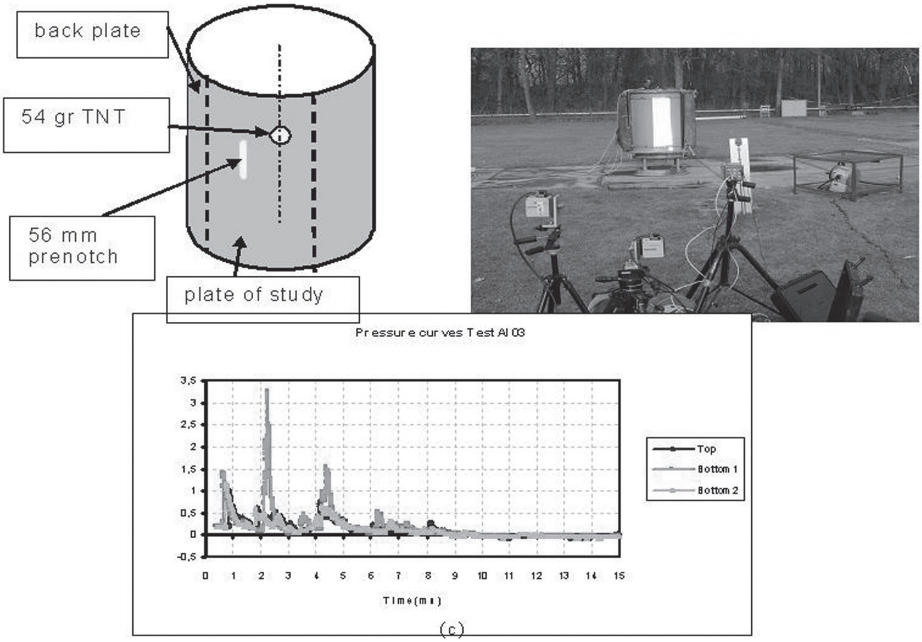

Figure 6: (a) sketch of pressurized barrel test; (b) barrel setup and high speed cameras; (c) measured blast pressure inside the barrel.

Figure 7 shows the barrel after the explosion, a close-up of the crack and the crack speed versus crack. Failure occurred in a ductile manner, with crack perpendicular to the maximum hoop stress (mode-I), and relatively low crack speeds. The average crack speeds were 300 m/s. SEM images show the typical dimple like structure, characteristic of ductile fracture.

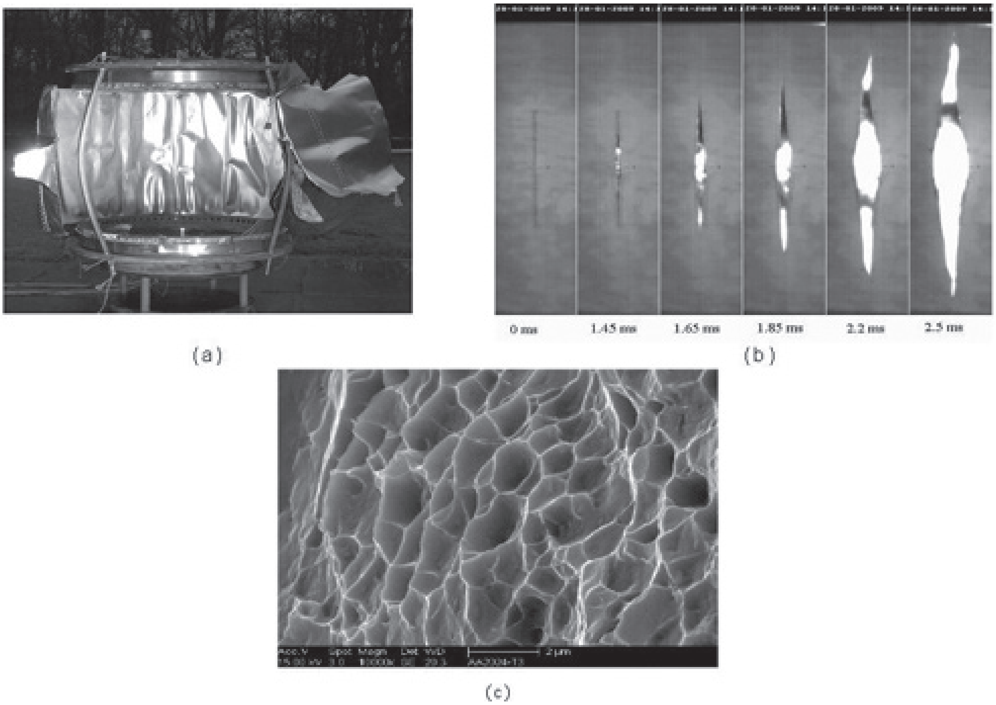

Figure 7: (a) Aluminium barrel after explosion; (b) high speed camera snapshots during crack propagation; (c) SEM image of the fracture surface.

4. Simulations

To better understand the fracture process, numerical simulations of the barrel test experiments have been performed. Fracture was modelled using cohesive zone elements. It turned out that static fracture toughness overpredicts the crack speed. Hence, a newly developed viscoplastic cohesive zone model is used [4], which has been implemented in the nonlinear finite element code LS-DYNA [5]. Using one set of material parameters, the model is able to reproduce static as well as dynamic tests. The model can capture the increase in fracture toughness with loading rate which is observed in experiments [6]. This effect is seen in Figure 8, which shows the rate effect on the traction-opening law.

Figure 9 shows a sequence of Von-Mises stress contour plots during crack propagation. The cohesive elements have been placed along the expected, vertical, crack path, in between the shell elements which are used to model the barrel. Figure 10 shows the simulated and experimental

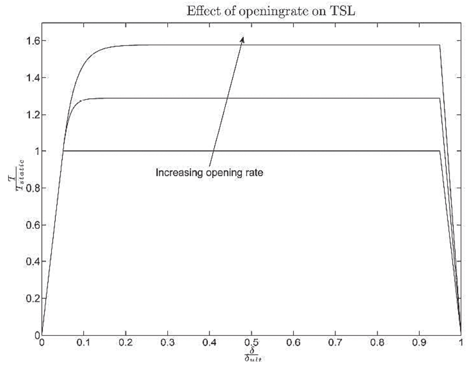

Figure 8: Perzyna viscoplastic cohesive zone model for dynamic crack propagation, showing load rate sensitivity.

crack velocity versus crack length curves and the crack length versus time. The agreement is quite reasonable, considering the uncertainty in the blast load.

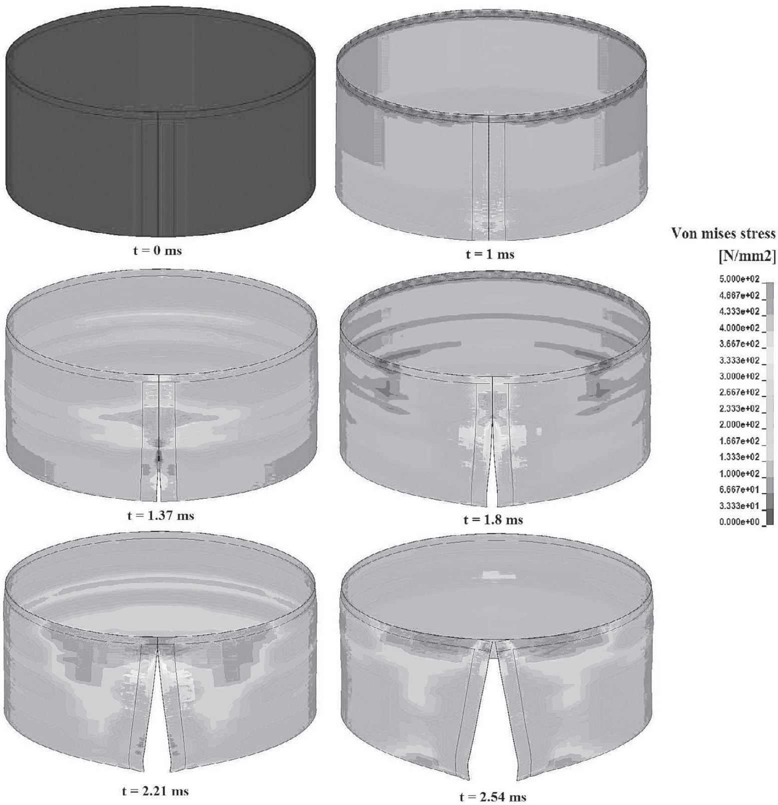

Figure 9: Von-Mises stress contour plots during crack propagation of the barrel test.

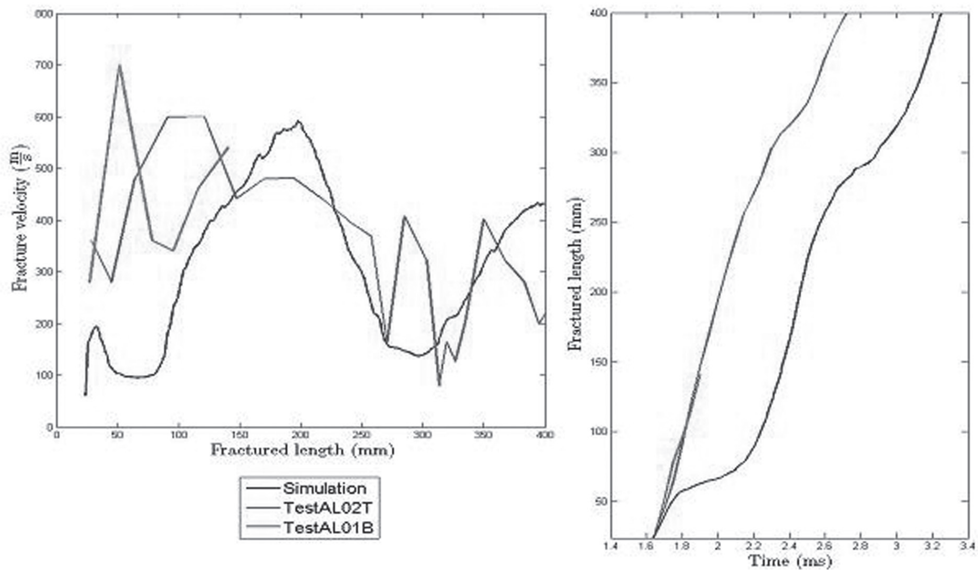

Figure 10: (left) Fracture velocity-fracture length; (right) fracture length-time.

Conclusions

To characterize the mechanical behaviour of airplane fuselage material AA2024-T3 under dynamic loading, dynamic tensile tests and fracture tests have been performed. The main conclusions are summarized below.

1-Dynamic tensile tests.
AA2024-T3 shows no strain rate effect, constant failure strain and failure strength upon different strain rates.

The servo-hydraulic tests are preferred over the LSM tests, since they show less structural dynamic effects, and allow reaching higher strain rates can be attained, up to 200 1/s, while the LSM test just 20-30 1/s.

2-Dynamic crack propagation tests.
The prestressed plate tests prove not to be suitable for monitoring crack propagation, due to a lack of symmetry, undesirable effects caused by the explosive charge (out of plane displacement and unknown extent of damage around the crack tips).

The barrel tests on the other hand allow monitoring the mode-I crack propagation and measure the crack speed of the different material tested. Aluminium displayed a ductile behaviour, with moderate crack velocities.

3-Computer simulations.
The barrel tests and the computer simulations using a rate dependent cohesive zone model were

in good agreement. The model can capture the increase in toughness with an increasing loading rate.

References

[1] European-Comission. *VULCAN-STREP-FP6*. 2005 [cited; Vulnerability analysis for near future composite/hybrid airstructures: hardening via new materials and design approaches against fire and blast due to accidents or terrorist attacks]. Available from: http://ec.europa.eu/research/transport/pdf/aero_report_en.pdf.

[2] Kroon, E., *Dynamic tensile strength of FM94 S2-glassfiber composite*. 2009, TNO.

[3] van Aanhold, J.E., A.F.J. Weersink, and J.W.L. Ludolphy. *Dynamic testing of adhesive joints using a shock testing machine*. in *69th Shock & Vibration Symposium*. St. Paul MN, USA,.

[4] van der Meulen, R., et al. *Cohesive modeling of ductile dynamic failure of pressurized metallic structures*. in *12th international conference on fracture*. 2009. Ottawa, Canada.

[5] Hallquist, J.O., *LS-DYNA keyword's user manual, version 971*. 2007: Livermore software technology corporation.

[6] Couque, H., *Effect of loading rate on the plane stress fracture toughness properties of an aluminum alloy.* Journal de physique, 1994. **IV**.