The shock and spall response of AA 7010-T7651

P J Hazell[1], G J Appleby-Thomas[2], D C Wood[2] and J D Painter[2]

[1]School of Engineering and Information Technology, UNSW Canberra, The University of New South Wales, Northcott Drive, Canberra, ACT 2600, Australia
[2]Cranfield Defence and Security, Cranfield University, Shrivenham, Swindon, SN6 8LA, UK

E-mail: p.hazell@adfa.edu.au

Abstract. We have subjected the aluminium alloy 7010-T7651 to shock loading. A heterodyne velocimeter system was used to interrogate both the HEL and dynamic tensile failure (spall). It was shown that the HEL in the short transverse direction is higher than in the longitudinal direction whereas the spall strength is higher in the longitudinal direction. The increased HEL in the short-transverse direction is thought to be due to the increased number of grain boundaries due to the highly elongated nature of the grains along the rolling direction. The spall strength was measured and compared with other high-strength aluminium alloys and was found to be 1.61 GPa ± 0.19 GPa in the longitudinal direction and 1.20 GPa ± 0.01 GPa in the short-transverse direction.

1. Introduction

The aluminium alloy 7010-T7651 (Al+Zn+Mg+Cu) is a high-strength aluminium alloy manufactured by solution treatment, stretching for stress relief and then artificially over-aged to achieve some corrosion resistance with a moderate reduction in strength [1]. This particular alloy is a contender for armour applications given its reasonable strength and toughness values. This alloy is also used extensively in aerospace structures – most recently for some of the wing components on the Airbus A380 [2].

The shock response to aluminium has been extensively studied for decades. However, more recently the shock behavior of certain alloys that are relevant to armour applications have been studied by Boteler et al. [3, 4], Whelchel et al. [5] and Appleby-Thomas et al. [6]. The shock behavior of AA 7010-T6 has been studied by Edwards et al. [7], with subsequent modelling work carried out by Vignjevic et al. [8].

In this work we examine the shock response of AA 7010-T7651 to shock-wave loading using the plate-impact method. The Hugoniot elastic limit (HEL) and spall strength in both the longitudinal and short-transverse directions were interrogated.

2. Experimental

Plate-impact testing was carried out on a 5 m, 50-mm bore single-stage gas gun using aluminum (AA 6082-T6) plates of 4-mm thickness; the target thickness was nominally 8 mm. The AA 7010-T7651 targets were shocked either along the longitudinal direction or through the short-transverse direction of the plate. Transmission of the shock wave was evaluated using a Heterodyne velocimeter (Het-v). The system employed a 12 mW laser source (DFB-1550-BF-20-2.5-FA) operating at 1545±15 nm. An ITC-510 laser diode combi-controller was used to control both the temperature and the supply current to the laser diode, ensuring a stable output wavelength. The interfered light was collected by a PDA8GS amplified photodetector, having 8 GHz bandwidth. A disposable experimental probe was employed consisting of a collimating lens connected to a 5 m length of 9/125 μm single-mode fibre.

The elastic wave velocities were measured using a Panametrics 5077 PR pulser-receiver in the pulse-echo mode. These results, along with the derived shear modulus (*G*) and Poisson's ratio (ν) are presented below in table 1.

Table 1. Elastic data.

Sample	c_l **(mm/μs)**	c_s **(mm/μs)**	c_b **(mm/μs)**	***G*** **(GPa)**	***ν***
Longitudinal	6.420	3.101	5.329	27.0	0.348
Short-transverse	6.411	3.106	5.314	27.1	0.347

Strength properties were measured using an Instron 1122 (High Wycombe, UK). Measured values of the yield strength (Y), ultimate tensile strength (UTS) and elongation at failure (El.) are presented in table 2 (± 1 standard deviation). This data compares well with mechanical data published in the literature [9].

Table 2. Quasi-static strength data.

Sample	***Y*** **(MPa)**	***UTS*** **(MPa)**	***El.*** **(%)**
Longitudinal	464 ± 13	541 ± 11	15.7 ± 0.6
Short-transverse	426 ± 19	527 ± 9	8.0 ± 1.0

3. Results and Discussion

3.1. Measurement of the HEL

HEL measurements were carried out by measuring the free-surface particle velocities at the rear of the target using the Het-v system. The HELs were calculated from the free-surface velocity measurements using the following equation:

$$\sigma_{HEL} = \frac{1}{2}\rho_0 c_l u_{fs} , \tag{1}$$

where ρ_0 is the initial density (2.81 g/cc) and u_{fs} is the free-surface velocity taken from the point at which the elastic wave transitions to the plastic wave. The results are shown below in table 3 presented with error calculated to ±1 standard deviation. In addition, the results are compared to the gauge values provided by Edwards et al. for the T6 alloy [7].

Table 3. HEL data.

Sample	**This work – HEL (GPa)**	**Ref. [7] – HEL (GPa)**
Longitudinal	0.89 ± 0.02	1.25
Short-transverse	0.95 ± 0.02	1.06

Our data is somewhat lower than the data for AA 7010-T6 presented by Edwards et al. [7]. The reason for this may lie in the different temper. Notably it should be pointed out too that our Het-v data shows a measureable increase in the HEL in the short-transverse direction when compared to the longitudinal direction. This is contrary to the quasi-static (tensile) yield behavior and the results of Edwards et al. [7]. This has, however, been seen in a strain hardened 5083 alloy by Whelchel et al. [5] as well as other alloys. In our 7010 alloy, the grains were highly elongated in the direction of rolling and therefore in the short-transverse loading direction there is an increased grain-boundary density. In compression, this will lead to an increased level of dislocation impediment (due to more grain boundaries being present) and therefore strengthening. Whereas in tension, it has been shown that micro-porosity along the grain boundaries of an aluminium alloy affects its tensile properties [10]; the quasi-static tensile strength data reflects this.

3.2. Spall behaviour

The spall behavior was assessed at various stress levels by changing the impact stress in both the longitudinal and short-transverse loading directions. Figures 1 and 2 show the traces. There are several points to note from these shock traces. Firstly, it is seen that at the lowest shock stress (~ 1.3 GPa) that the short-transverse target spalled whereas the target shocked in the longitudinal direction did not. Secondly, as the shock stress is increased there is nominally a constant level of velocity drop for both sets of targets (although the short-transverse targets exhibited a small declanation as the shock stress was increased).

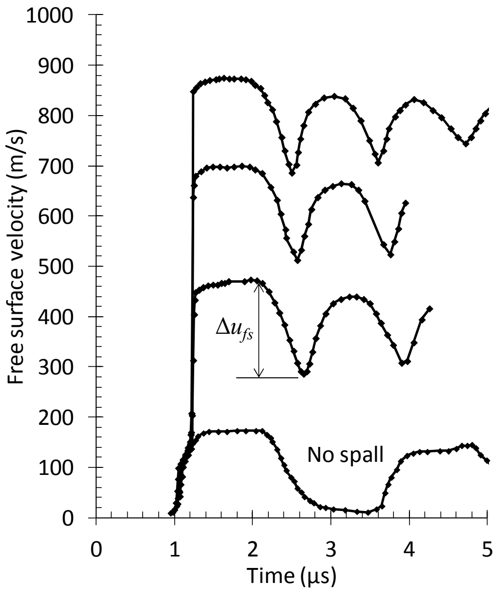

Figure 1. Free-surface velocity traces for samples shocked along the longitudinal direction.

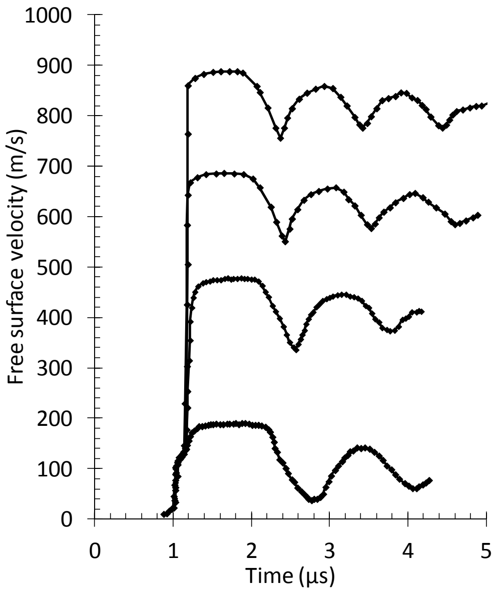

Figure 2. Free-surface velocity traces for samples shocked in the short-transverse direction.

Calculation of the spall strength (σ^*) was carried out using the following equations [11]:

$$\sigma^* = \frac{1}{2}\rho_0 c_b(\Delta u_{fs} + \delta)\,, \tag{2}$$

$$\delta = \left(\frac{x}{c_b} - \frac{x}{c_l}\right)\frac{|\dot{u}_1\,\dot{u}_2|}{|\dot{u}_1| + \dot{u}_2}, \tag{3}$$

where x is the spall position, $\dot{u}_1$ is the gradient of the velocity curve into the spall dip and $\dot{u}_2$ is the gradient out of the spall dip. Delta (δ) is the correction to the free-surface velocity and was 16% (± 7%) of the maximum free-surface velocity measurements for the longitudinal shots and 16% (± 5%) for the short-transverse experiments (± 1 standard deviation). These values are higher than the typical values cited by Kanel et al. [12] for aluminium and magnesium (~ 10%).

Results are presented in figure 3. As anticipated the spall strength in the longitudinal direction is shown to be higher than that of the spall strength values in the short-transverse direction by ~ 30%. The longitudinal spall strength in the longitudinal direction and was 1.61 GPa ± 0.19 GPa; it was 1.20 GPa ± 0.01 GPa in the short-transverse direction (± 1 standard deviation). The increased spall strength in the longitudinal direction mirrored the quasi-static tensile strength values. It should be noted that the work of Edwards et al. [7] showed varying behavior as the shock stress was increased whereas our results indicate that the alloy exhibited a more classical spall response. At this stage the reason why this is so is unclear however it should be noted that Edwards et al. used a different experimental set-up to us.

Comparing these results to that of Boteler et al. [3], shows that this alloy exhibits a higher spall strength than the AA 5083-H131. Boteler et al. reported a mean spall strength of 0.94 GPa using the equations listed above. Similarly Welchel et al. [5] reported a maximum spall strength in the longitudinal direction of 1.06 GPa versus 0.95 GPa in the transverse directions. They also noted, however, that the target thickness and the flyer-plate thickness affected these values.

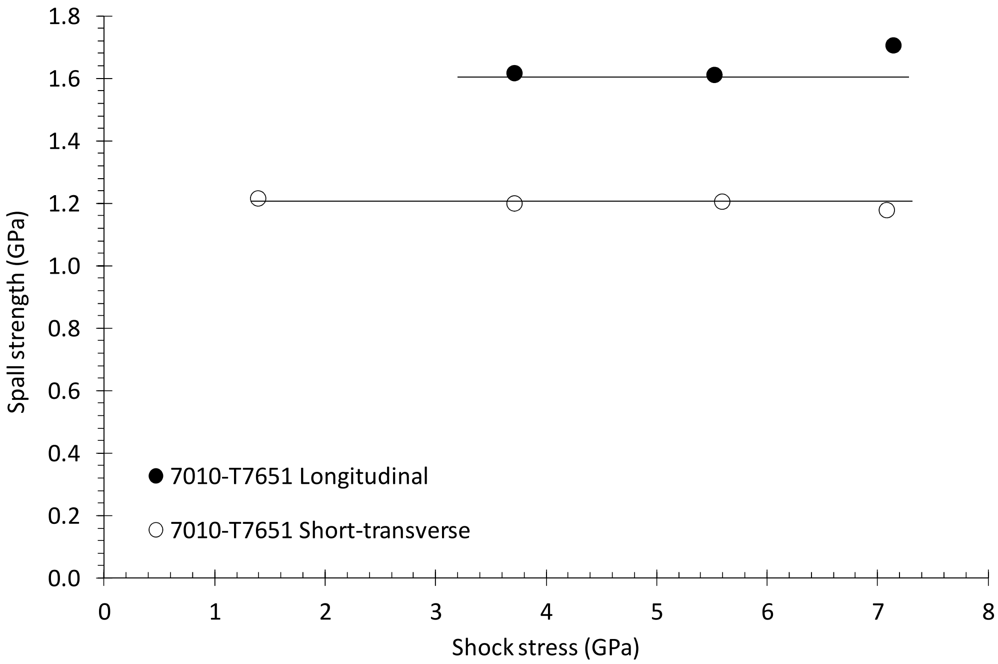

Figure 3. Calculation of the spall strength for varying shock stress.

3.3 Microscopy

Samples were recovered from a tube of cotton rags after being shocked. They were then etched, and sectioned to examine the failure modes. No spall failure was observed at a shock stress of ~ 1.3 GPa in the longitudinal direction whereas in the short transverse direction spall failure was evident. The spall crack in the central plane of the target appeared to be brittle in nature and followed the direction of the grain boundaries. This was also true of the longitudinally shocked samples that showed a blocky type of fracture path. Further, for the samples shocked in the longitudinal direction it appeared that voids had opened up in-between the grain boundaries before linking up to form the spall crack.

4. Conclusions

The AA 7010-T7651 has been shocked using the plate-impact method. It was shown that:

- The HEL appeared higher in the short-transverse direction than in the longitudinal direction with the Het-v recording values of 0.95 GPa ± 0.02 GPa in the short-transverse direction and 0.89 GPa ± 0.02 GPa in the longitudinal direction. It is thought that this is due to the increased number of grain boundaries in the short transverse loading direction thereby leading to the observed strengthening.

- The shock stress at which incipient spall occurred was higher in the longitudinal direction.
- The longitudinal spall strength appeared markedly higher in the longitudinal direction and was 1.61 GPa ± 0.19 GPa; it was 1.20 GPa ± 0.01 GPa in the short-transverse direction.

Given the relatively high HEL (particularly in the short-transverse direction) and the high spall strength when compared to other high-strength aluminium alloys, it appears that this alloy's mechanical response under dynamic loading makes it a reasonable choice for armour applications.

Acknowledgements
The authors would like to acknowledge the contributions of Mr Andrew Roberts and Mr Adrian Mustey of Cranfield University for help with the experiments and microscopy. Professor Ian Horsfall is also thanked for providing the material. We also thank Mr Vinod John who worked on this material for his MSc thesis and helped with some of the experiments and microscopy studies. PJH would also like to thank Professor Stephen Yeomans of UNSW for useful discussions.

References

[1] Benedyk J C 2010 *Light Met. Age* **68** 16
[2] Lequeu P, Lassince P and Warner T 2007 *Adv. Mater. Processes* **165** 41
[3] Boteler J M and Dandekar D P 2007 *AIP Conf. Proc.* **955** 481
[4] Boteler J M and Dandekar D P 2006 *J. Appl. Phys.* **100** 054902
[5] Whelchel R L, Kennedy G B, Dwivedi S K, Sanders J T H and Thadhani N N 2013 *J. Appl. Phys.* 113 233506
[6] Appleby-Thomas G J and Hazell P J 2010 *J. Appl. Phys.* **107** 123508
[7] Edwards M R, Bourne N K and Millett J C F *AIP Conf. Proc.* **620** 523
[8] Vignjevic R, Bourne N K, Millett J C F and De Vuyst T 2002 *J. Appl. Phys.* **92** 4342
[9] Schra L and Hart W G J 1983 *Eng. Fract. Mech.* **17** 493
[10] Li X, He L, Cao Y, Zhu P, Guo Y and Cui J 2012 *Adv. Mat. Res.* **422** 627
[11] Antoun T, Seaman L, Curran D R, Kanel G I, Razorenov S V and Utkin A V 2003 *Spall Fracture* (New York: Springer)
[12] Kanel G I, Razorenov S V, Bogatch A, Utkin A V, Fortov V E and Grady D E 1996 *J. Appl. Phys.* **79** 8310