Development of an Interrupted Pulse Expanding Ring Test

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Abstract

An interrupted pulse electromagnetic (EM) expanding ring test is being developed at the University of Waterloo to study the high rate behaviour of sheet metals. In a classic EM expanding ring test, a ring is expanded radially using the forces induced on the ring by a high frequency high intensity current flowing in a nearby coil. If the driving force and the acceleration of the ring are known, then the stress-strain history of the ring can be determined. Coil currents are typically generated by large capacitor banks that produce a current discharge in the shape of a damped sinusoid. To properly determine the stress of the ring, the forces induced on the ring by the current pulse must be known, which is difficult to do in practice. The approach taken in this work is to interrupt the current by means of an exploding wire switch to eliminate the Lorentz forces and achieve a free flight condition, where the stress can be determined using only the measured velocity and density of the ring. The velocity of the rings was measured using a photon Doppler velocimeter (PDV). With this technique significant periods of free-flight were obtained, with the corresponding stress-strain data. Results for 1.5 mm sheet of AA 5182-O are presented.

Keywords

High rate testing, Expanding ring test, Interrupted pulse

1 Introduction

The need to reduce vehicle weight has resulted in considerable interest in the application of aluminum alloys and advanced high strength steels in automotive mass production. Unfortunately, these materials exhibit only moderate formability when compared to traditional low carbon steel alloys. Several researchers have shown that the formability of some of these alloys can be increased using high speed forming techniques (Balanethiram and Daehn, 1994, Imbert et al., 2005 and Imbert and Worswick, 2012). The reasons behind the increased formability are not yet clearly understood. This is in part due to lack of understanding of the material properties at the strain rates that can be encountered during these process, which have been predicted to be in excess of 10,000 s-1, (Imbert et al., 2005, Imbert and Worswick, 2012). This leads to significant limitations on the ability to model these processes. The expanding ring technique is one of a few with potential to generate the stress-strain data at the high rates needed to produce the accurate material models required.

An ideal expanding ring test generates uniaxial tensile stresses and high strain rates within a sample ring, by causing it to expand radially at high speeds (**Fig. 1**). If the ring acceleration is known, the deformation is only radial, and the driving force is known the then stress-strain behaviour is relatively easy to determine.

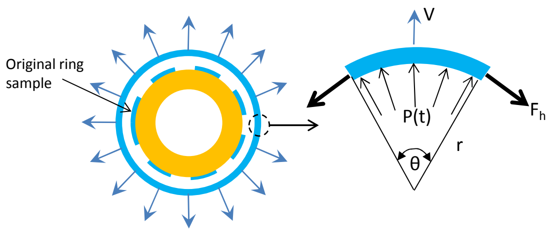

***Figure 1**: Basic principles of the expanding ring test*

The stress, strain and strain rates for an expanding ring are given by (Hoggatt and Recht, 1969, Imbert et al. 2015):

$$\sigma = \quad -\frac{(\rho\theta r\ddot{r} + F_{p(t)})}{A\theta} \tag{1}$$

$$\varepsilon = \frac{\Delta r}{r} \tag{2}$$

$$\dot{\varepsilon} = \frac{\varepsilon}{\Delta t} = \frac{\dot{r}}{r} \tag{3}$$

Where σ=stress, ε= strain,$\dot{\varepsilon}$=strain rate ρ=density, $r = radius$, $\ddot{r}$ = radial acceleration and $F_{P(t)}$ = force generated by the driving pressure P(t). In EM expansion tests, $F_{P(t)}$ are the induced Lorentz forces. If there is no driving force, i.e. free-flight, **Eq. 1** becomes;

$$\sigma = \rho r\ddot{r} \tag{4}$$

The test requires accurate radial acceleration measurements, which are difficult since radial velocities can exceed 100 m/s and test durations are in the order of 50 µs. The advent of the Photon Doppler Velocimeter (PDV) (Strand et al. 2006, Landen et al. 2009) has made these measurements significantly easier to obtain.

Ring expansion tests have been in use since the 1960's (Johnson, 1962, Hoggatt and Recht, 1969), but have never been widely implemented. Currently, the two preferred ways of performing the test are the EM expansion (Gourdin,1989 and Gourdin et al., 1989) and the exploding wire techniques (Rajendran and Fyfe, 1982). In EM expansion, the ring is accelerated by the forces induced on it by a current flowing through a nearby spiral coil. It is effective for high conductivity, relatively low strength materials. To determine the stress-strain behaviour, the induced forces are needed, which can be very difficult to determine.

In the exploding wire test, the ring is expanded by an elastomer (the “driver”) that is itself expanded by vaporizing a wire located in its centre using a high frequency high current pulse (Rajendran and Fyfe, 1982, Johnson et al., 2010). The test eliminates the effects of conductivity, since it does not rely on induced forces. However, the driving force produced by the driver is difficult to determine, as is the exact interaction between the driver and the specimen.

Sheet metal poses challenges to the expanding ring technique, due to the anisotropy of the material and the difficulty of obtaining specimens that accurately represent the properties of the parent sheet metal. To the authors’ knowledge, there is not a complete understanding of how to obtain accurate constitutive data from sheet metal using the expanding ring test. This work is part of an effort to develop such a test for AA 5182 and DP 600 sheet metal. Both the EM and exploding wire techniques were studied and tested and it was determined that an interrupted current EM ring expansion test had the greatest potential for being developed into a reliable test (Imbert et al., 2015). By interrupting the current pulse, the ring is allowed to achieve free-flight, thus eliminating the need to determine the induced forces, significantly reducing the uncertainty of the stress-strain behaviour obtained. The following sections describe the test developed, the numerical analysis used to gain insight into the tests and the experimental and numerical results.

2 Experimental Methods

2.1 Apparatus

A schematic view of the expanding ring apparatus is shown in **Fig. 4**. It consists of a capacitor bank called the magnetic pulse generator (MPG), a coil, Rogowski coils to measure coil and ring currents and a PDV to measure the sample velocity. An aluminum wire is placed in the circuit to act as an exploding switch.

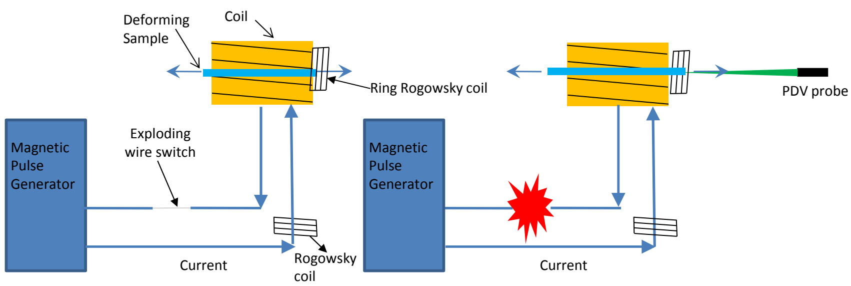

Figure 4: *Schematic of the experimental apparatus*

2.1.1 Magnetic Pulse Generator

A Pulsar MPW 20 Research Edition MPG, with a nominal maximum energy capacity of 20 kJ and a maximum charging voltage of 9,000 volts was used. The machine capacitance is

539.7 µF, inductance is 24.35 nH, and resistance is 2.98 mΩ. The nominal shorted discharge frequency was 24.51 kHz. For the present work the MPG was charged to 4.0 kV, which results in a stored energy of 4.3 kJ.

2.1.2 Pulse interruption

Interrupting the current pulses used for expanding ring tests, which have frequencies above 10 kHz and peaks currents in the order of 100 kA, is very difficult. Mechanical switches are not capable of handling these conditions. Solid state devices could potentially be used, but the authors were unable to source a device that met the requirements. Gourdin (1989) used a shaped explosive charge switch to interrupt the current by creating an alternate current path. Switches based on exploding aluminum foil were developed by Bealing and Carpenter (1972) to interrupt and shape pulses.

For this research, aluminum wires of 0.8 mm diameter were chosen to interrupt the pulse. The wires ignited once a certain current value was reached, thus opening the circuit. **Fig. 5** shows a current pulse from a discharge using a closed copper circuit, along with five interrupted pulses achieved with the exploding wire switch. The interrupted pulses deliver less energy than the full pulses, due to some energy going to ground as the circuit is opened and, to a lesser extent, the energy consumed by the wire explosion.

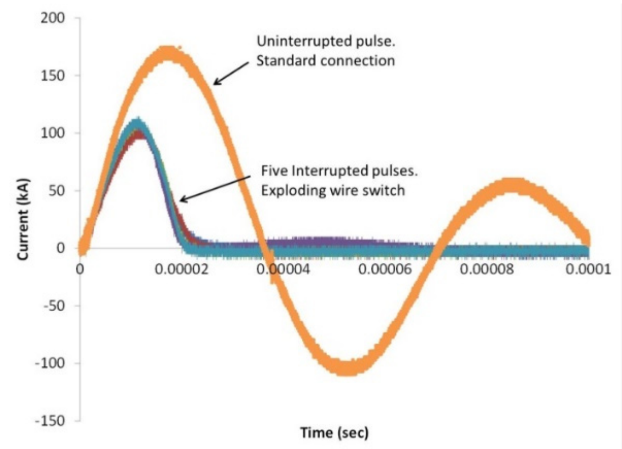

Figure 5: *Comparison of uninterrupted and five interrupted current pulses*

2.1.3 Measurements of the Sample Velocity

The sample velocity was measured using an Ohio Manufacturing Institute PDV, which uses a 1550 nm in wave length fibre optic laser. The basic principles of the PDV are given by Strand et al. (2006). The PDV outputs a voltage versus time signal. The frequency spectrum of the signal was calculated using Matlab©. The velocity was calculated using the method outlined in by Strand et al. (2006,) as implemented by Imbert et al. (2015).

2.1.4 Coil

A single turn copper coil was designed for this work (**Fig. 7**). The goal of the design was to reduce the coil impedance, maximize strength and minimize out-of-plane sample deformation. Simulations showed that the rings expanded with the single turn coil had less out of plane deformation when compared to rings expanded with a 3-turn spiral coil (**Fig. 8**).Two coil designs were tested, one with internal grooves (**Fig.7-a**) and one with no grooves (**Fig. 7-b**). The grooved design was morere efficient, but was structurally weaker, so the design with no grooves was chosen. Coils with 38 mm and 25.4 mm outer diameter ("d" in **Fig. 7**) were built to obtain different strain rate histories, as per **Eq. 3**.

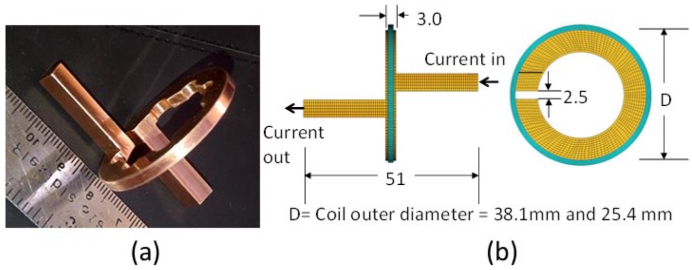

Figure 7: *Coil design developed for present work. All dimensions in mm.*

Figure 8: *Predicted shapes for rings formed with the single turn and a 3-turn spiral coil*

2.2 Material and Sample Geometry

The material tested in this work was 1.5 mm sheet of AA 5182-O, which has a nominal yield strength of 130 MPa. Detailed constitutive characterization of this material at strain rates up to 1,000 s^{-1} is reported by Rahmaan et al. (2014). Samples were cut from the stock material and made with a square cross section, of side lengths equal to the sheet thickness.

3 Numerical Modelling

Numerical models were used to gain insight into the general behaviour of the rings during the tests. The 38 mm ID ring tests were modelled. An EM capable version of LS-Dyna (L'Eplattenier et al. 2009) was used. The mesh used is shown in Fig. 7-b. Both the coil and ring were modelled with brick elements. The ring was modelled with 5 elements through both thickness and width, which resulted in 6,250 elements. The coil was modelled with 10 elements through thickness and width, for a total of 16,000 elements. An experimentally measured current profile was used as the current input. The rate sensitive modified Voce material model for AA 5182-O developed by Rahmaan et al. (2015) was used. The model provided good predictions of the coil and ring currents (**Fig. 9)** and the final ring geometry (**Fig. 10**).

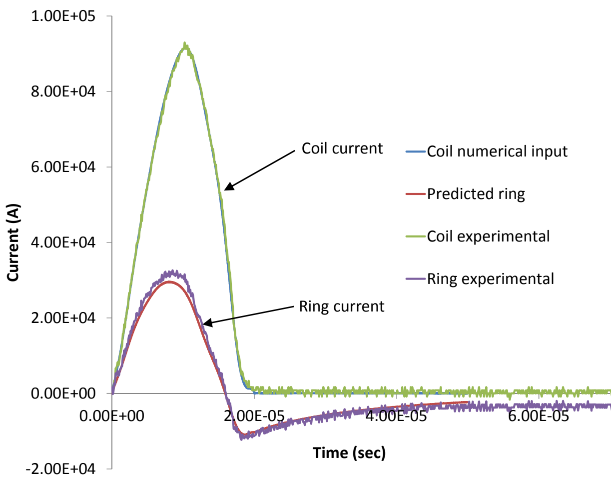

Figure 9: *Measured and predicted coil and ring currents*

The Johnson-Cook (J-C) (Johnson and Cook, 1985) material model was used to study the effects of thermal softening on the ring. Although limited, the J-C model has been shown capable of capturing the general flow stress behaviour of aluminum alloys at rates up to 1,500 s^{-1} (Smerd et al. 2005).The J-C implementation used for this work requires an equation of state (EOS). To the authors' knowledge there is no available J-C and EOS parameter set available for AA 5182-O in the literature. To overcome this, the J-C parameters from Meyer (1996) and EOS parameters from Steinberg (1996) for AA 2024-T351 were used. Both adiabatic and Joule heating were taken into consideration. The authors recognize the limitations of this approach; however, it was deemed acceptable since the goal was to determine if the test could be affected by thermal softening and not to accurately model the AA 5182 behaviour.

4 Results and Discussion

Rings formed using the 38 mm and 25.4 mmm coils are shown in **Fig. 10**. The tested samples present a distinctive shape that the numerical simulations indicate is mainly the result of the 2.5 mm gap discussed above (Fig. 10-c).

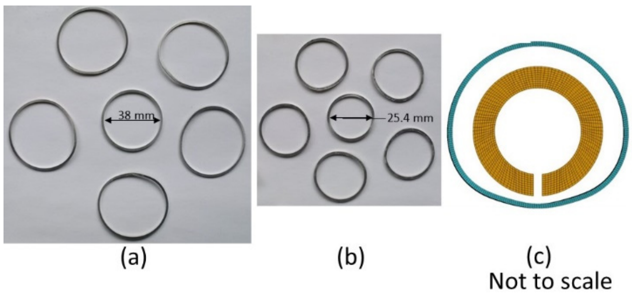

Figure 10: *Rings expanded with (a) the 38 mm and (b) the 25.4 mm diameter coils surrounding an un-deformed ring. The final predicted shape of an expanded ring (c)*

Experimental strain rate and stress data for five samples each tested with the 38 mm and 25.4 mm coil are shown in **Fig. 11**. The stresses are calculated using **Eq. 4**. The point where the current pulse stops and free-flight begins is indicated with a line and shows that a significant period of free-flight was achieved. No stress data is presented prior to free flight, since **Eq. 4** is not valid for that part of the test. There is relatively good repeatability, especially given the nature of this experiment. Data from Smerd et al. (2005) for AA 5182-O at 1,500 s^{-1} at 23 C° and 300 C° is presented for comparison.

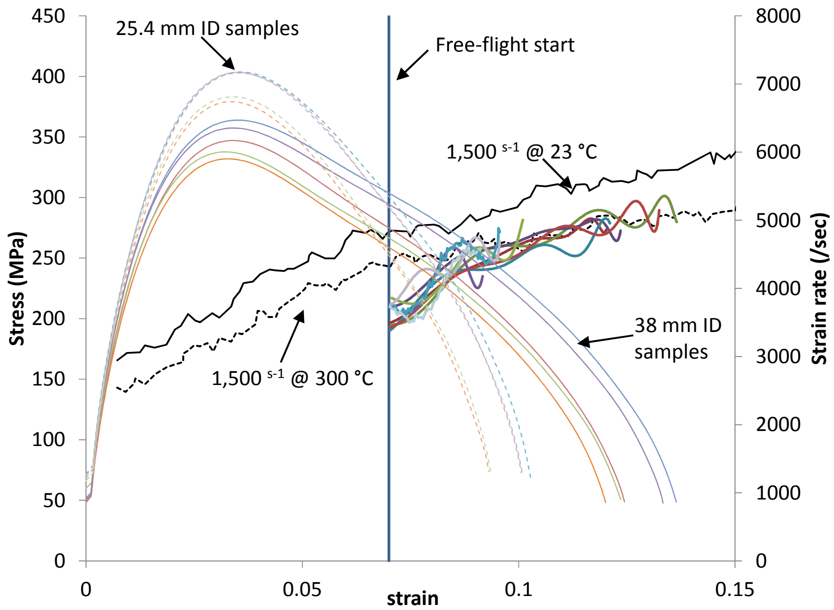

Figure 11: *Strain rate and stress versus true strain for the five 38 mm ID and five 25.4 ID sample. Data for 1,500* s^{-1} *from Smerd et al. (2005)*

The highest strains recorded were approximately 7,000 s^{-1} and were experienced by the 25.4 mm ID rings. The highest strain rates for the 38 mm ID rings was approximately 6,000 s^{-1}. The highest strain rates were achieved while there was still current in the circuit. The strain rates decrease to approximately 5,000 s^{-1} at the start of free-flight, and to approximately 1,000 s^{-1} at the end of the test. The observed strain rate decay poses some challenges to data fitting for constitutive modelling.

All the experimental stresses obtained are close to each other and closely follow the high temperature data published by Smerd et al. (2005). This suggests the possibility that thermal softening may be affecting the stress response. Since adiabatic heating is not expected to raise the temperature of the samples to a degree where softening will occur, the possibility that Joule heating is affecting the sample was explored.

4.1 Joule Heating and Thermal Softening

Joule heating refers to the heat generated on a body by a current flowing through it. Gourdin (1989) recognized that Joule heating could result in thermal softening and designed an interrupted pulse experiment to minimize it. Using ring current measurements and an analytical analysis Gourdin (1989) concluded that the combined Joule and adiabatic heating effects were minimal. Gourdin's analysis and measurements assumed uniform current distribution through the sample. Henchi et al. (2008) presented numerical simulations that showed that the current distributions within the samples were not uniform. **Fig. 11** shows simulations of the current test, which predict that the current distribution is not uniform.

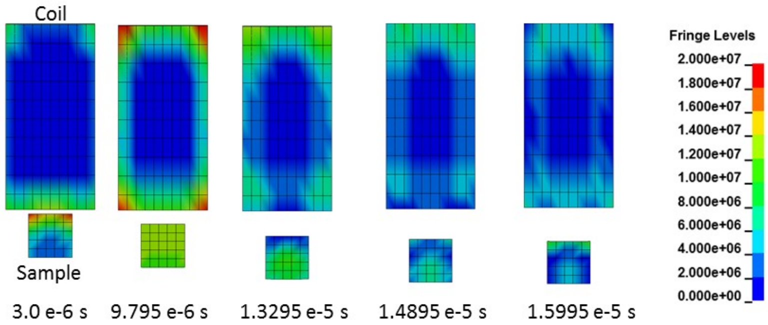

***Figure 11**: Current density distribution of the coil and sample. Contours are of µJ/mm³*

The results shown in Fig. 12 suggest that thermal effects soften the material and make the stress distribution along the ring non-uniform. Although the results are preliminary, if this were the case, it would mean that thermal softening has a significant effect and that the basic assumption of a tensile test, i.e. uniform stress distribution, is violated during an EM expanding ring test (see inset in **Fig. 12**). This would not disqualify the EM expanding ring test from consideration as means to obtain constitutive data, but it means that a methodology combining experimental, finite element and optimization techniques as proposed by Henchi et al. (2008) and Johnson et al. (2010) will likely be needed to extract accurate data from these types of tests. Work is ongoing to confirm these results.

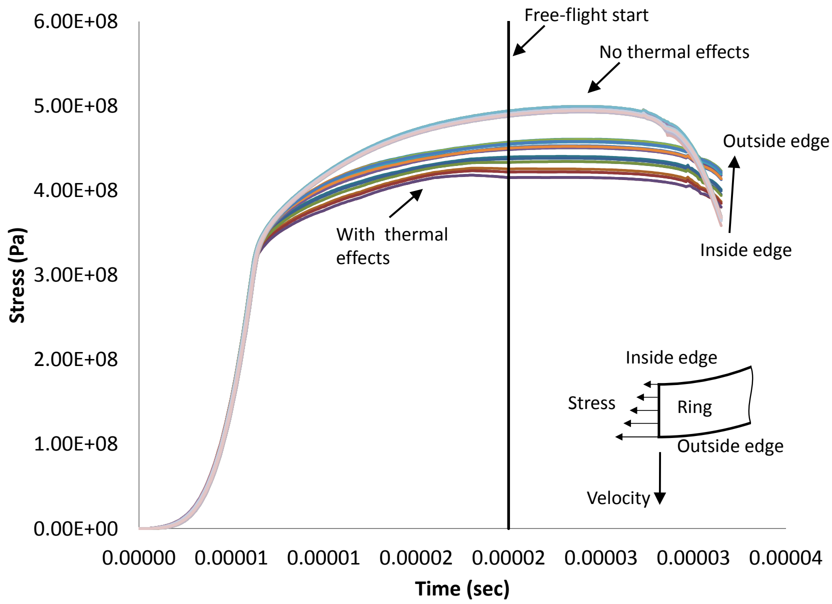

***Figure 12:** Predicted V-M stresses vs. time along the ring cross section from simulations with and without thermal effects. The inset shows an illustration of the stress state.*

5 Conclusions

The following conclusions were reached:

1. The interrupted ring expansion test results in free-flight of the ring, from which stress-strain data can be determined without the need to take into account the driving force.
2. The highest strains occur while there is still induced forces on the ring. Thus, the driving force must be taken into account to determine the stress-strain response at the highest strain rates.
3. The strain rates during the test are not constant, which pose a challenge for constitutive fitting.
4. The free flight stress-strain data suggest that thermal softening may be occurring.
5. Simulations suggest that thermal softening is taking place and that the rings present non-uniform stress distributions through the cross section. Work is ongoing to implement more accurate material models, like the one proposed by Bardelcik et al. (2012), which incorporates an exponential hardening term.
6. Given conclusions 2 and 4 finite element and optimization methods will likely be required for accurate data extraction from these types of tests.

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