# Numerical Study of an Interrupted Pulse Electromagnetic Expanding Ring Test

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## Abstract

*Light weighting of vehicle structures will play an important part in the efforts to reduce fuel consumption and enable alternatively powered vehicles. The use of aluminum alloys and advanced high strength steels is one potential way of achieving significant weight reductions in the short to medium term. One of the main challenges posed by these materials is their relatively poor formability when compared with traditional automotive steel alloys. High speed forming has been studied as a way of increasing the formability of these alloys, with promising results. The lack of accurate constitutive data and models for these materials at the strain rates encountered in high speed forming, which can exceed 1,000 $s^{-1}$, presents a significant challenge to their implementation. Expanding ring tests have been used to measure the stress strain response at materials at high strain rates. In principle, these tests generate a uniaxial tensile stress state within the ring. If the driving force is known and the acceleration of the sample can be measured, then the stress and strain response of the material can be obtained. Significant challenges need to be overcome to obtain stress-strain data from this test, namely understanding the induced forces, Joule heating and the actual stress distribution in the ring. An interrupted pulse electromagnetic expanding ring test is being developed at the University of Waterloo to study the high rate behaviour of sheet metals. The test minimizes the induced forces generated on the sample and can produce free flight conditions. Given the complex nature of the phenomena and the speed at which they occur, numerical simulations play a critical role in analyzing the test. This paper presents the results of a multi-physics numerical analysis of the test based on a 3-D simulations using LS-DYNA®. This analysis has been done to determine the effect of Joule heating and the driving force on the data generated by the test.*

## Introduction

The push to reduce fuel consumption has resulted in considerable interest in utilizing aluminum alloys and advanced high strength steels to reduce the weight of mass produced vehicles. Unfortunately, these materials exhibit only moderate formability when compared to traditional low carbon steel alloys. High speed forming techniques have been shown to have increased the formability of these type of alloys under certain conditions (Balanethiram and Daehn, 1994, Imbert *et al.*, 2005 and Imbert and Worswick, 2012). The mechanisms that result the increased formability are poorly understood, due, in part, to a lack of understanding of the material stress-strain response at the strain rates produced by these process, which predictions have shown can be in excess of 10,000 $s^{-1}$, (Imbert *et al.*, 2005, Imbert and Worswick, 2012). This makes it very difficult to accurately model these processes. The expanding ring test (Fig. 1) is one of a few techniques that can potentially generate stress-strain data at the high rates encountered in high speed forming processes.

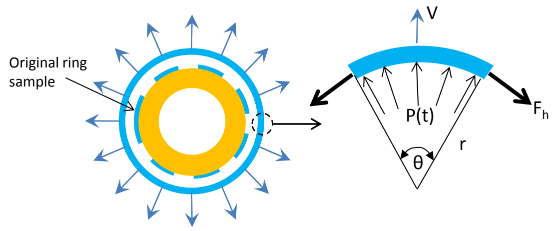


**Figure 1:** Basic principles of the expanding ring test.

In an ideal expanding ring test, a uniaxial tensile stress state and high strain rates are generated within a sample ring, by causing it to expand radially at high speeds (Fig. 1). The tress-strain response of the ring material can be determined if the ring only expands radially and its acceleration and driving force are known, using the following equations (Hoggatt and Recht, 1969, Imbert *et al*. 2015):

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

$$\varepsilon = \frac{\Delta r}{r} \quad (2)$$

$$\dot{\varepsilon} = \frac{\varepsilon}{\Delta t} = \frac{\dot{r}}{r} \quad (3)$$

Where $\sigma$=stress, $\varepsilon$= strain, $\dot{\varepsilon}$=strain rate $\rho$=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;

$$\sigma = \rho r\ddot{r} \quad (4)$$

It is evident from the above equations that accurate radial acceleration measurements are needed, which present significant challenges to obtain  given that radial velocities can exceed 100 m/s and test durations are in the order of 50 µs. The Photon Doppler Velocimeter (PDV) (Strand *et al.* 2006, Landen *et al.* 2009) has made it possible to directly measure velocities during expanding ring tests, with relative ease. The velocity data can then be differentiated to obtain the acceleration.

Ring expansion tests for studying materials at high rates were introduced in the 1960's (Johnson, 1962, Hoggatt and Recht, 1969).  Presently, tests are typically performed using the EM expansion (Gourdin, 1989 and Gourdin *et al.*, 1989) and the exploding wire (Rajendran and Fyfe, 1982) techniques. EM expansion uses the forces induced on the ring by a current flowing through a nearby spiral coil to achieve very high ring accelerations. The process is ideal for high conductivity, relatively low strength materials, e.g. aluminum. To determine the stress-strain behaviour, the magnitude and direction of the induced forces are needed, which can be very difficult to determine.

The exploding wire test expands the sample rings by using a cylindrical "driver", typically an elastomer like urethane that is expanded by vaporizing a wire placed along its centre axis by exposing it to a high frequency high current pulse (Rajendran and Fyfe, 1982, Johnson *et al.*, 2010). The test does not rely on induced forces, thus eliminating its dependence on the conductivity of the material. The driving forces generated are difficult to measure or calculate, as are the friction and other forces generated between the driver and specimen.

Sheet metal poses challenges to the expanding ring technique and, 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. Difficulties stem from material anisotropy and the difficulty in obtaining specimens, as described by Imbert *et al.* (2015) and Imbert and Worswick (2016). This work describes the numerical modelling being undertaken to develop a viable expanding ring test for sheet metal. The aluminum alloy AA 5182 was used for this study. After analyzing and testing the EM and exploding wire techniques an interrupted current EM ring expansion test was chosen for further development (Imbert *et al.*, 2015 and Imbert and Worswick, 2016). The interruption of the current pulse, produces a free-flight conditions on the ring, reducing, in principle, the uncertainty of the stress-strain data obtained, since no induced forces are present. Given the complexity of the process and the speeds at which it takes place, numerical analysis is critical to obtaining an understanding of the behaviour of the material. The remainder of the paper will provide a description of the test and the numerical models being used to better understand it.

## Experimental Methods

Fig. 4 shows an illustration of the interrupted pulse EM expanding ring apparatus, which 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 was placed in the circuit to act as an exploding switch. The MPG used was 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. 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.

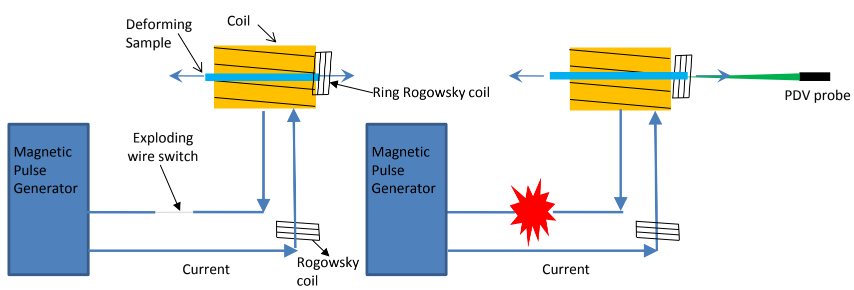


**Figure 4:** Schematic of the experimental apparatus (Imbert and Worswick, 2016).

The pulses were interrupted by using "exploding" switches made from 0.8 mm diameter aluminum wires, which vaporized at specific current values, opening the circuit. Typical coil and ring currents from an interrupted pulse test are shown in Fig. 5.

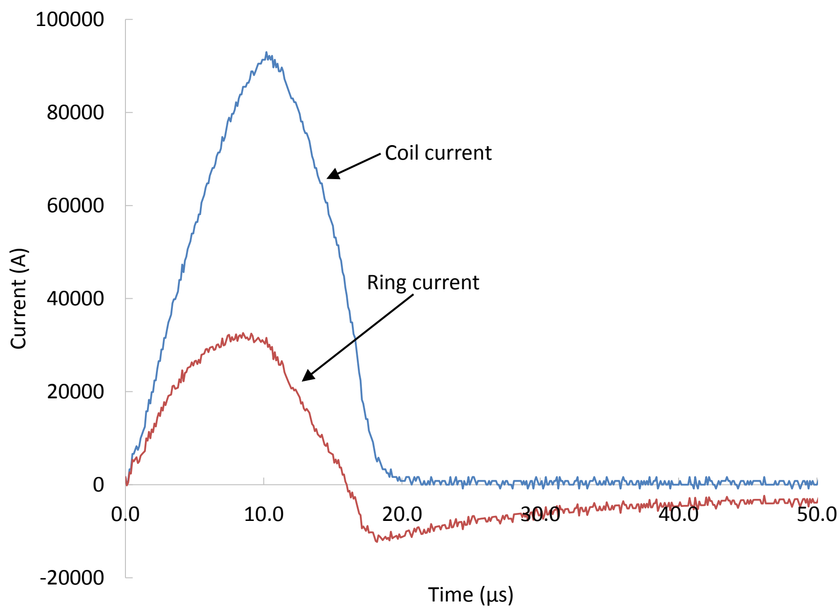


**Figure 5:** Experimental coil and ring currents from an interrupted pule EM expanding ring test.

The single turn copper coil shown in Fig. 6 was used, which was designed to reduce coil impedance, maximize strength and minimize out-of-plane sample deformation. Simulations show produced less out of plane deformation when compared to a 3-turn spiral coil (Imbert and Worswick, 2016). Results from experiments performed with the 38 mm outer diameter coil are used for the present work.

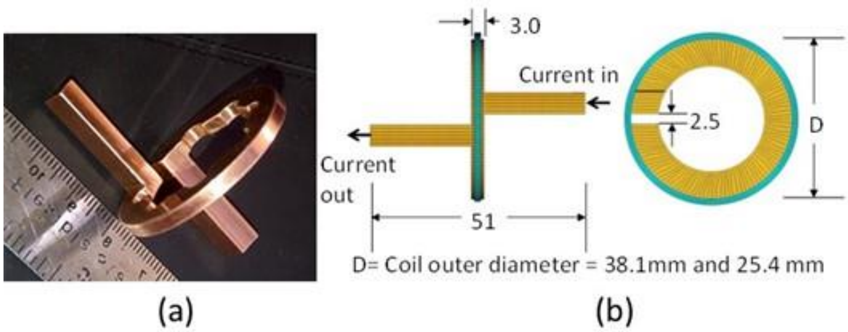


**Figure 6:** Single turn copper coil used (Imbert and Worswick, 2016).

The ring 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 velocity was calculated using the method outlined in by Strand *et al.* (2006,) as implemented by Imbert *et al.* (2015). More details and background on the experimental apparatus and methodology are presented by Imbert and Worswick (2016).

The material tested in this work was 1.5 mm sheet of AA 5182-O, which has a nominal yield strength of 130 MPa. Samples were cut from the stock material and made with a square cross section, of side lengths equal to the sheet thickness. Detailed constitutive characterization of this material at strain rates up to 1,000 $s^{-1}$ is reported by Rahmaan *et al.* (2014). Experimental strain rate and stress data for five samples each tested with the 38 mm and 25.4 mm coil are shown in Fig. 7 (Imbert and Worswick, 2016). The vertical line indicates the point where free-flight begins

No stress data is presented prior to free flight, since Eq. 4 is not valid for that part of the test. 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. The highest strains recorded the 38 mm ID rings was approximately 6,000 $s^{-1}$.

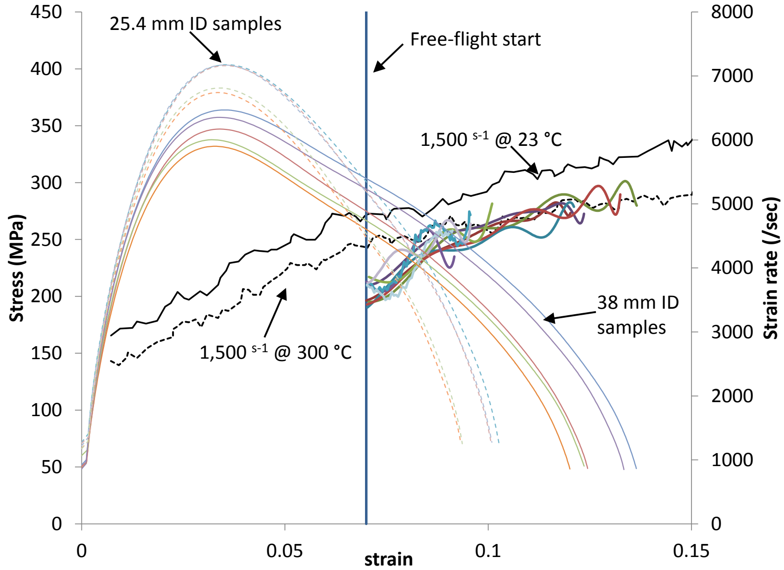


**Figure 7:** Strain rate and stress versus true strain for the five 38 mm ID and five 25.4 ID sample. Data for 1,500 $s^{-1}$ from Smerd et al. (2005). (Imbert and Worswick, 2016).

## Numerical Modeling

The test was modelled using the EM modules of LS-DYNA (L'Eplattenier *et al.* 2009). An experimentally measured current was used as an input for the model and applied to the coil. The mesh used is shown in Fig. 6-b, with details of the elements shown in Fig. 8. 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. The coil was modelled as an elastic copper with artificially high strength, to simplify the model. Two material models were used to model the ring, a rate sensitive model for AA 5182 and a rate and temperature sensitive model for AA 2024.

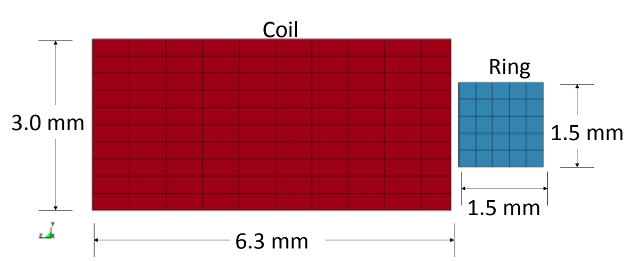


**Figure 8:** Measured and predicted coil and ring currents

No material model for AA 5182 is known to the authors that can accurately capture the material behaviour at the strain rates shown in Fig. 7. The rate sensitive modified Voce material model for AA 5182-O developed by Rahmaan *et al.* (2015) was used to validate the model and explore the behaviour of the ring and coil system during the tests. Model run times were approximately 52 hours of CPU time using eight processors.

The experimental data shown in Fig. 7 suggest that thermal softening may be affecting the material. To study the effects, if any, of thermal softening the Johnson-Cook (J-C) (Johnson and Cook, 1985) material model was used, which, despite its limitations, has been shown capable of capturing the general flow stress behaviour of AA 5182 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. This approach could obviously not provide accurate information on AA 5182, but would be able to provide insight into the thermal softening effects of the process. Model run times were approximately 45 hours of CPU time using eight processors.

## Results and Discussion

A comparison of the experimental and predicted final shape of the rings is shown in Fig. 9. The simulations were able to captured the distinctive final shape of the tested samples and indicate is mainly the result of the 2.5 mm gap shown in Fig. 6-b. Fig. 9 also indicates the location were the data from the simulations were extracted from for this work. A comparison between the measured and predicted coil and ring currents is shown in Fig. 10, which shows good agreement with the experimental results. The ring current for Fig. 10 was extracted using a numerical Rogowski coil, which measured the resultant current through the ring, which is consistent with the experimental measurements. The coil and ring currents varied slightly between tests, so the comparisons show the experimental results compared to models were the experimental current for the actual test were used as inputs.

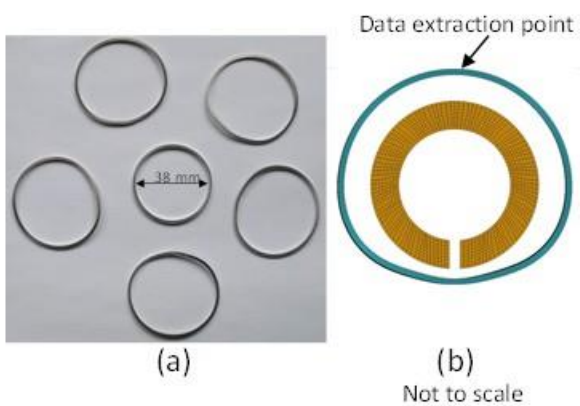


**Figure 9:** Rings expanded experimentally surrounding an un-deformed ring (a) and the final predicted shape of an expanded ring (b).

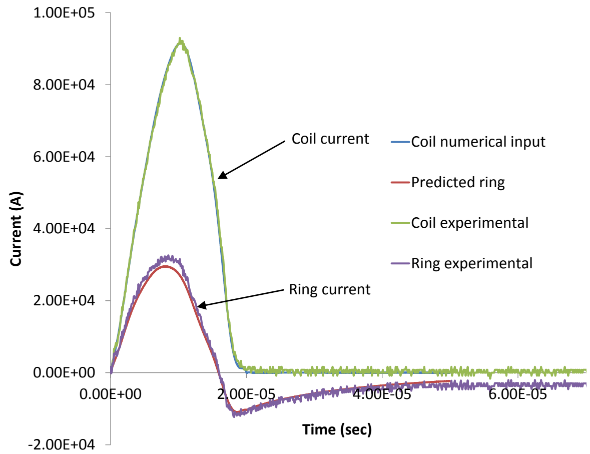


**Figure 10:** Measured and predicted coil and ring currents (Imbert and Worswick, 2016).

Predicted and experimental velocity and effective stress are shown in Fig. 12 and 13, respectively. Both the predicted velocity and stress are higher than the measured values. This is likely due to the limitations of the material model used.

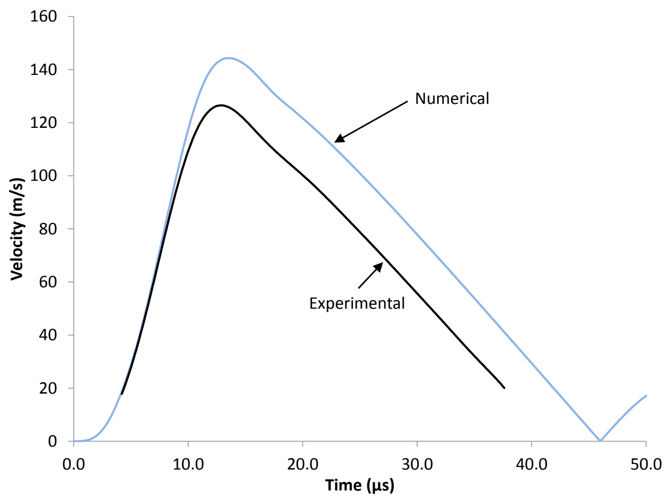


**Figure 12:** Predicted velocities with the modified Voce model and measured ring velocities.

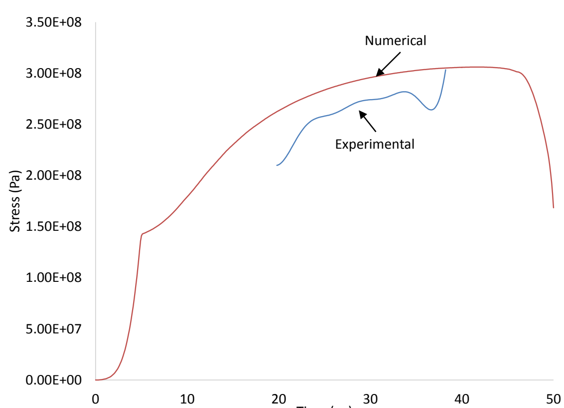


**Figure 12:** Predicted stresses with the modified Voce model and measured stresses. Experimental stresses are only shown for the area where eq. 4 is valid.

The results from the simulations that used the J-C model suggest that Joule heating affects the test. Fig. 13 shows simulations of the current test, showing that the current distribution is not uniform, which agrees with the results from Henchi *et al.* (2008). The non-uniform current distribution leads to an un-even temperature distribution, were the temperature on the inside of the ring is higher than the outside, as shown in Fig. 14,

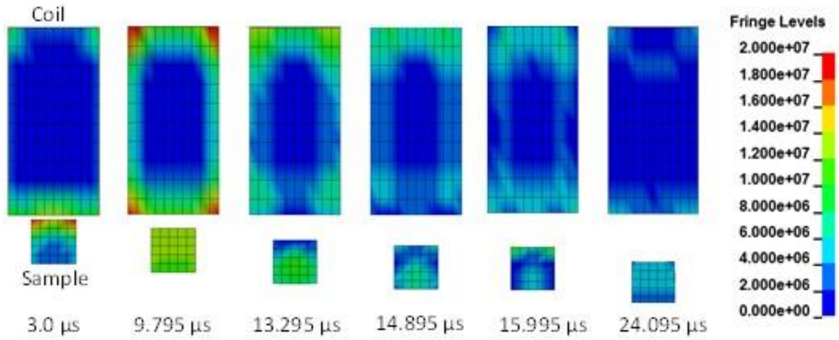


**Figure 13**: Current density distribution of the coil and sample. Contours are of µJ/mm$^3$.

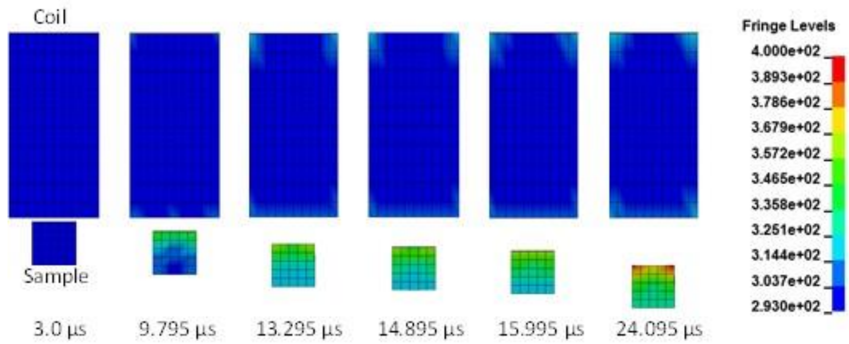


**Figure 14**: Temperature distribution of the coil and sample. Contours are of K°.

The results shown in Figs. 13 and 14 suggest that thermal effects are present and support the data reported by Imbert and Worswick (2016) that showed non-uniform predicted stress distributions along the ring (Fig. 15). If thermal softening makes the stress distributions non-uniform, the tests violates the uniform stress distribution assumption of a tensile test (see inset in Fig. 15). This would not disqualify the EM expanding ring as a potential material characterization test, but it would mean that to obtain accurate data methodologies combining experimental, finite element and optimization techniques as proposed by Henchi *et al.* (2008) and Johnson *et al.* (2010) will likely be needed for the tests to provide accurate and reliable data. The limitations of the material models used make these results preliminary and ongoing research aims to confirm these results.

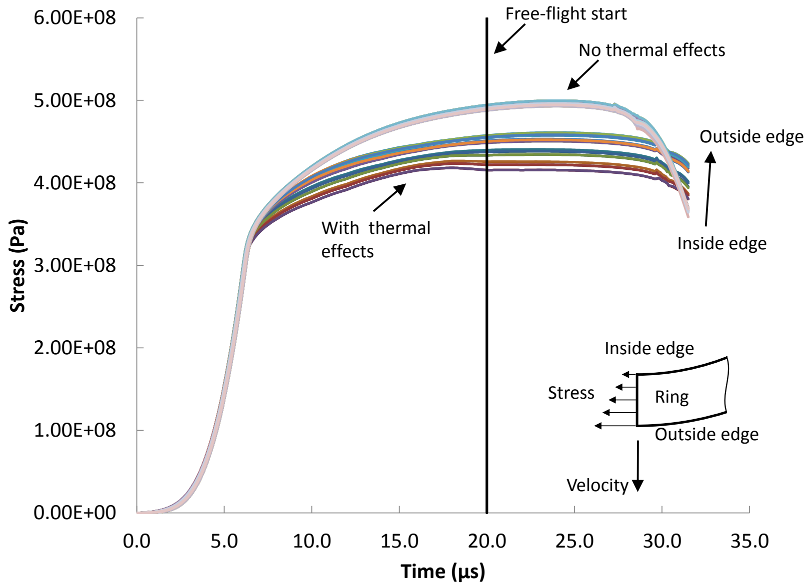


**Figure 15:** Predicted V-M stresses vs. time along the ring cross section from simulations with and without thermal effects. The inset shows an illustration of the stress state (Imbert and Worswick, 2016).

## Conclusions

The following conclusions were reached:

1. The model accurately predicts the induced ring currents and final shape of the ring.
2. Ring velocities and stresses are over predicted by the modified Voce model used.
3. The J-C models suggest that thermal softening is affecting the test
4. More accurate material models that incorporate thermal effects should be implemented.
6. Finite element and optimization methods will likely be needed to determined accurate stress strain responses from these type of tests.

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