HETEROGENEOUS DEFORMATION DURING ELECTROMAGNETIC RING EXPANSION TEST

K. YANG*, D. CHERNIKOV†, T. SAPANATHAN*,#, R.N. RAOELISON+, V. GLUSCHENKOV†, N. BUIRON* AND M. RACHIK*

*Sorbonne universités, Université de technologie de Compiègne, Laboratoire Roberval
CNRS UMR - 7337, Centre de recherche Royallieu, CS 60319, 60203 Compiègne cedex, France
Web page: http://www.utc.fr

† Samara National Research University, 34 Moskovskoye shosse, Samara, 443086, Russia
Web page: http://www.ssau.ru

#Institute of Mechanics, Materials and Civil Engineering, Université catholique de Louvain, B-1348 Louvain-la-Neuve, Belgium
Web page: http://www.uclouvain.be

+ Université de Bourgogne Franche Comté, IRTES-LERMPS, Université de Technologie de Belfort Montbéliard, 90100 Belfort, France
Web page: http://www.utbm.fr

Corresponding author: kang.yang@utc.fr (K. Yang)

Key words: Ring expansion test, Multiphysics Problems, Electromagnetic pulse forming, Finite element method

Abstract. High speed forming methods become attractive in manufacturing and it significantly reduces the cost and energy requirements. Conventional manufacturing processes such as forging, forming, stamping and cutting of metals typically involve a strain rate of $10^2 - 10^4\ s^{-1}$ which includes high energy rate fabrication (HERF) methods [1]. During advanced manufacturing methods such as high speed forming and high speed welding processes, certain local regions (e.g. interfaces) of materials could also experience significantly high strain rate ($> 10^4\ s^{-1}$). In order to understand the physical behaviours of materials and to design/control/optimise, such manufacturing processes that require an appropriate technique to capture the material's viscoplastic property under the high strain rate deformation. Therein, the electromagnetic ring expansion test becomes a promising method to characterize the material behaviours under the high strain rate deformation. The ring expansion is caused by Lorentz force that is generated due to the magnetic induction on the ring. However, the realistic nature of the electromagnetic ring expansion test is quite complex because of the coupling physics between electromagnetic-thermal-mechanical components.

Therefore, in this study we evaluate certain controlling parameters which govern the fundamental behaviour of the electromagnetic ring expansion test. Particularly the rotation and inhomogeneous deformation of the ring are noticeably observed and these phenomena require extra attention.

With the aid of LS-DYNA® package and concurrent experimental verifications, the influencing factors which cause the rotation and inhomogeneous deformation were identified. The analysis shows that the asymmetry of axial compression and radial expansion caused by Lorentz force resulted from the asymmetry of the coil geometry. Following this detailed analysis, this paper proposes the methodologies to reduce the rotation and inhomogeneous deformation of the ring during the electromagnetic ring expansion test.

1 INTRODUCTION

Over the past few decades, electromagnetic ring expansion test has been considered to investigate material properties under high stain rate deformation [2-5]. This technique uses electromagnetic pulse to create Lorentz force that causes the expansion on a metallic ring or tube. During the test, the induced current flow through the ring and the plastic deformation of the material generate heat and thereby it leads to an increase in the temperature of the workpiece. Thus, in order to understand and model the complete physical phenomena, one should consider the multi-physics phenomena of electromagnetic-thermal-mechanical coupled problem.

The workpiece deformation during an electromagnetic ring expansion test occurs at a very high deformation speed (i.e. short duration of time), it requires sophisticated measuring techniques to make some observations and identify the material parameters. Nowadays, thanks to the technological advancements, direct observation using high-speed cameras and photonic Doppler velocimetry (PDV) [6] are widely used in electromagnetic forming research to capture the high speed deformation. However, finite element (FE) simulations provide the alternative solution to understand the realistic behavior and physical phenomena which occur during the test.

In reality, during a ring expansion test, inhomogeneous deformations occur in most of the cases which significantly influence the material parameter identification procedure. In one of our recent work, the suitability of ring expansion test to identify the material parameters was investigated [7]. In that particular study a shield block mechanism was proposed to eliminate the compressive Lorentz force that is one of the reason associated with the inhomogeneous deformation [7] . However, till to date, there exist a lack of research work on the problem of inhomogeneous deformation and its consequences on the material parameter identification. The present work mainly focuses on the causes of the heterogeneous deformation. In this paper, the problem is investigated and the reasons for inhomogeneous deformation are identified with the help of FE simulations. By developing a clear understanding the situation, which can lead to minimize and/or completely eliminate the effect of inhomogeneous deformation during the ring expansion test.

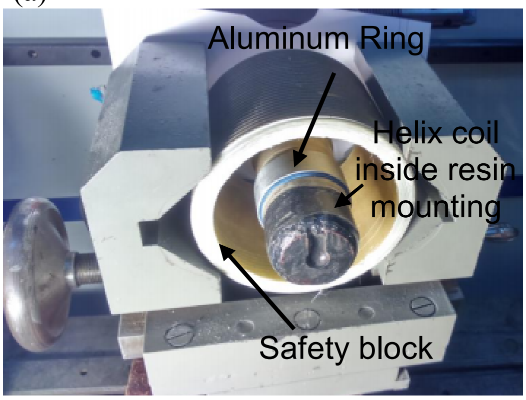
2 METHOD

2.1 Experiment method

The experimental test cases explained in this section were performed in Samara National Research University in Russia. The components of the experimental setup used in this study are shown in Figure 1.

(a)

(b)



(c)

Figure 1: Images showing the of experimental unit and its components (a) overall view of the apparatus, (b) Rogowski coil used for the electric current measurements (c) helix coil and the ring assembly placed insides a large safety block.

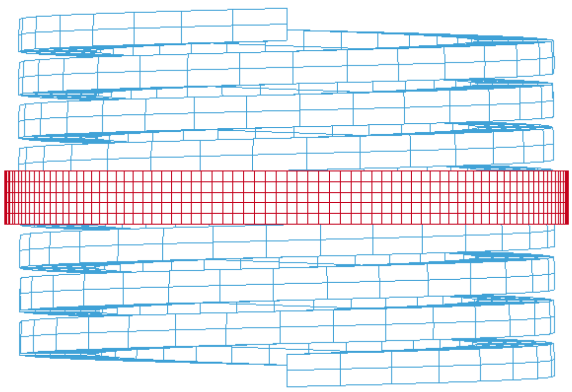
As shown in Figure 1, the major components of the equipment used in these experiments are the pulse generator, and a workstation including a helix coil (reinforced in a fiberglass resin), Rogowski coil and support used to hold the workpiece. The Rogowski coil [8] is used to measure the pulse current flow through the helix coil.

An 8-turn copper helix coil was used here to expand the ring. That has a cross section of *3 mm* × *7 mm* (height × radial direction) and winding pitch is *1 mm*. A shield block is also used for safety reasons to control the ejection of ring pieces at high energy from a fragmentation. Rings were made from an aluminum alloy AA5154 tube. They have an outer diameter of *52 mm*, having either *10 mm* or *5 mm* in height and *1 mm* in thickness. The maximum energy storage capacity of the power supply is *19.3 kJ*. In order to get a relatively high plastic strain without causing fracture, *1.27 kJ* and *1.83 kJ* energy pulses were respectively used for rings with *5mm* and *10 mm* heights. The frequency of current flow through the coil is ~*1.7 kHz*.

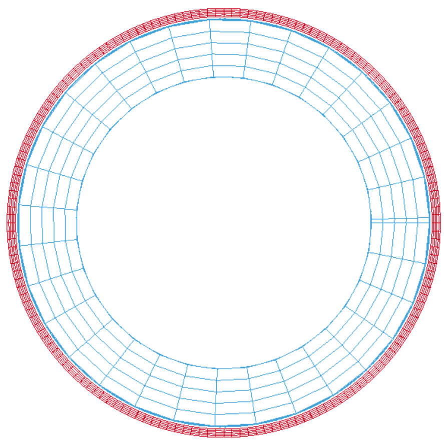
2.2 Simulation method

The LS-DYNA® Mechanical and Electromagnetic solvers were enabled to solve this coupled problem [9]. It use a boundary element method coupled with FE method to deal with the electromagnetic calculation [10, 11]. In this paper, LS-DYNA® solver ran on parallel computer network available at University of Technology of Compiègne, using multiple processors (16 Xeon X7542 processors with six-core at *2.67 GHz* (total of 96 cores) and *1 TB* RAM) configured in a Shared Memory Parallel (SMP) computation method.

The meshed models which consist of 8 nodes brick element for both coil and expansion ring were used in the simulation. The element size along the thickness of the ring was set as *0.2 mm*, which sufficiently captures the electromagnetic skin depth effect during the simulation. The element size along the height was set as *1 mm* that was also sufficient to capture the different amount of deformation along the height. The current flow through the helix coil is input to the model, and it was obtained from the experimental measurements using Rogowski coil. Figure 2 shows two different orientations of the meshed model for the case *5 mm* ring height.



(a)



(b)

Figure 2: Meshed model with *5 mm* rings used in LS-DYNA simulations (a) front view and (b) top view.

An appropriate plasticity model and the material properties are required for the simulation to predict an accurate test result. A standard rate dependent plasticity using Cowper-Symonds strain rate dependency model was used here to describe the material behaviors under high strain rate as shown in equation 1.

$$\bar{\sigma} = (\sigma_y + K\bar{\varepsilon}^n)\left[1 + \left(\frac{\dot{\bar{\varepsilon}}}{C}\right)^p\right] \tag{1}$$

where, $\overline{\sigma}$ and $\overline{\varepsilon}$ are the von Mises equivalent stress and strain respectively, $\dot{\overline{\varepsilon}}$ is the strain rate term and σ_y is the yield stress of the material. *K, n*, *C* and *p* are material constants given in Table 1. The coil was set as rigid and having fixed boundary condition in this simulation since it has been reinforced using a fiberglass resin mounting.

Table 1: Plasticity model parameters used for the ring material, AA5154

Parameters	*Yield stress (MPa)*	*K(MPa)*	*n*	*C*	*p*
Numerical values for AA5154	*177*	*625*	*1*	*6500*	*0.3333*

3 RESULTS

The final average diameters of *5 mm* and *10 mm* rings after the expansion are *59.4 mm* and *62.6 mm*, respectively. The final shapes of rings after expansion are shown in Figure 3. It is clearly noticeable that each specimen has a certain amount of inhomogeneous deformation.

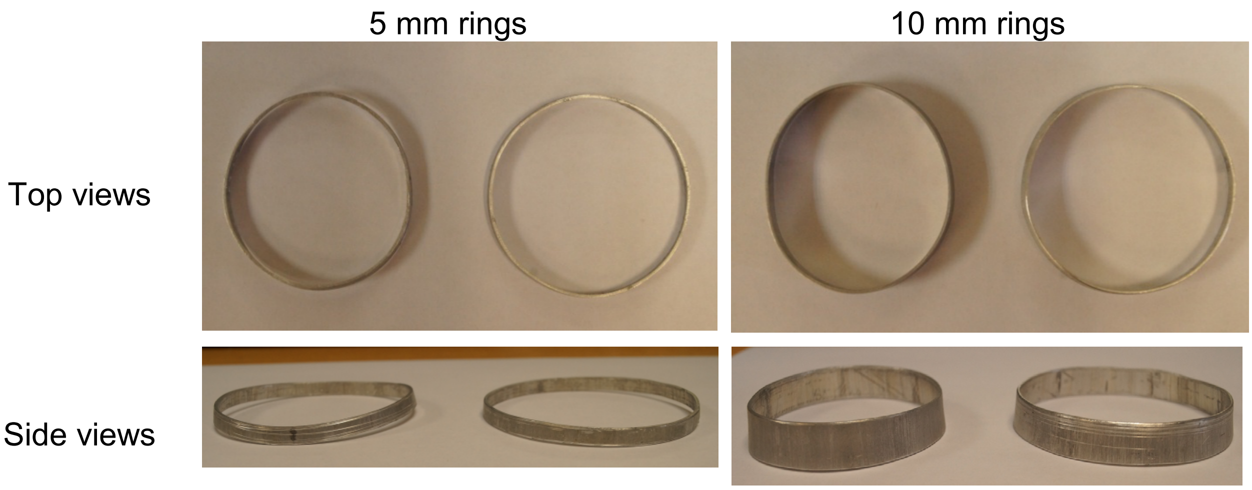


Figure 3: Top views and side views showing the final shape of rings after the expansion test

Although, the *5 mm* rings nearly remain round during the expansion process, they show an out of plane deformation in their side views. On the other hand, the *10 mm* rings have showed in-plane deformation, but the deformations on the top and bottom regions of those rings are clearly different.

Simulation results are also in a good agreement with experimental results as shown in Figure 4. The results have the final average diameters of *60.8 mm* and *63.1 mm* for the rings with *5 mm* and *10 mm* heights, respectively. The numerical simulation also shows some of the inhomogeneous deformation, *e.g.* out of plane deformations of *5 mm* rings. Comparing simulated results to experiments, the reason for inhomogeneous deformations will be discussed in the next section.

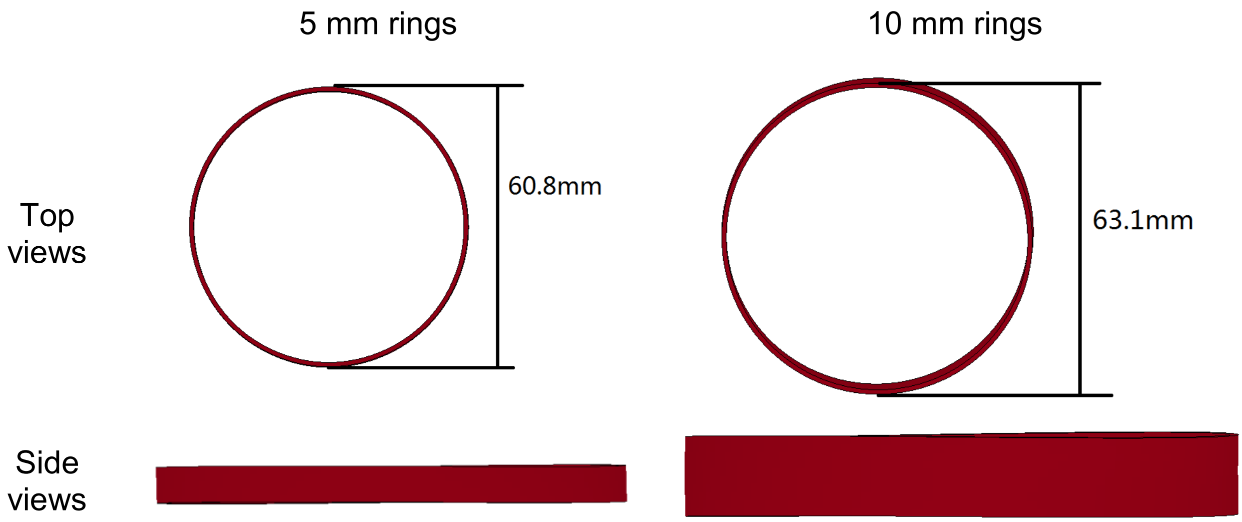
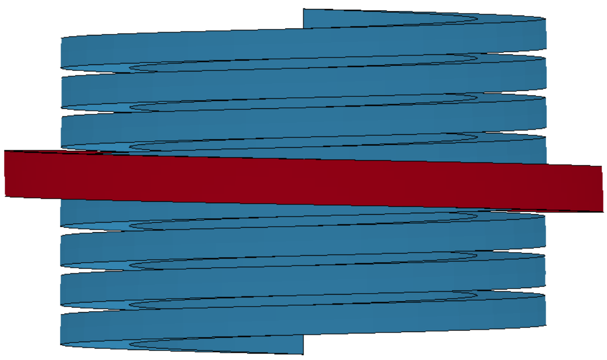


Figure 4: Simulation results showing the final geometry of the rings with *5 mm* and *10 mm* height at the end of the expansion test

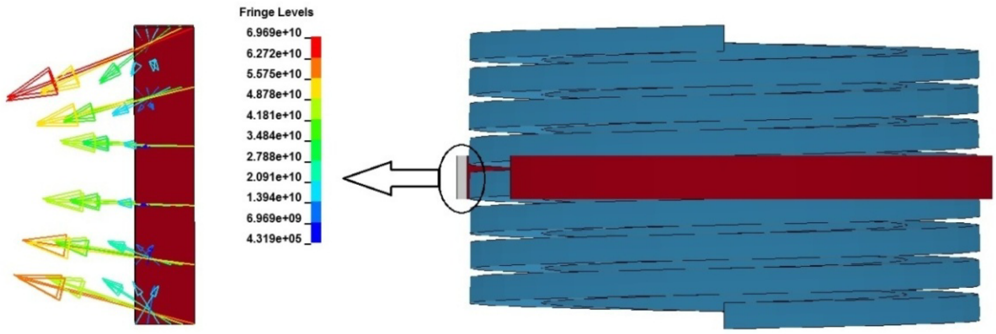
4 ANALYSIS OF INHOMOGENEOUS DEFORMATION

4.1 Rigid body rotation

In simulation, the rigid body rotation of rings can be easily observed. Figure 5a shows the simulation result of *5 mm* ring expansion test at the time step of *120 µs* (nearly at the end of input pulse current). During the process, the ring is rotated by an angle of *~5°* and thus Lorentz force causes out of plane deformation on the ring.



(a)



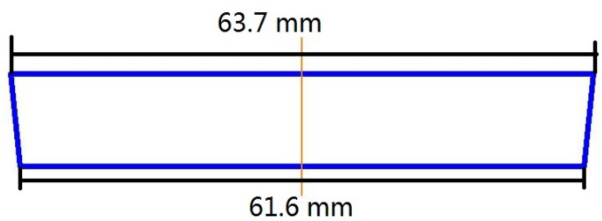
(b)

Figure 5: Simulation result of *5 mm* ring expansion test; (a) Relative location of ring and coil at *120 µs* and (b) Lorentz force vectors on a cross section on the ring (Unit: N/m^3).

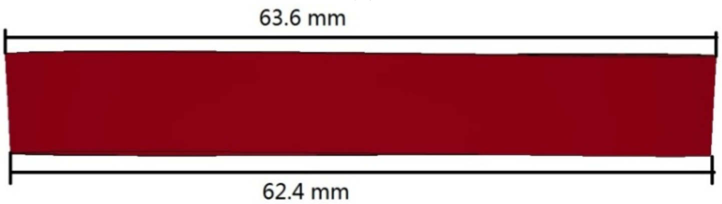
Figure 5b shows Lorentz force vectors on a ring cross section at *10 µs*. At this instant, the ring was not rotated. The vectors clearly indicate that there was not only a tensile Lorentz force (in the radial direction) but also a compressive Lorentz force acts on the ring. Besides, the maximum Lorentz force on the top region of the ring ($6.969x10^{10}\ N/m^3$) was bigger than that of on the bottom region of the ring (smaller than $6.272\ x10^{10}\ N/m^3$). This uneven distribution may be caused by the asymmetry of the coil and the relative longitudinal position of the ring. Vice versa, it also enables a rigid body rotation of the ring during the test.

4.2 Effect of longitudinally non concentric location of the ring

In the previous section the rigid body rotation has been discussed. However, it cannot cause uneven deformations on the top and bottom for *10 mm* rings as shown in Figure 3. Figure 6a shows a schematic illustration with the final dimension of an expanded *10 mm* ring obtained with a case of longitudinally non concentric location of the ring (i.e. Ring center longitudinally has an offset with the centerline of the helix coil).



(a)



(b)

Figure 6: Side view of the *10 mm* ring after the expansion test showing the final dimension (a) schematic illustration showing the results of experiment and (b) a non concentric simulation model.

The experimental results indicate that the top region of the ring has an outer diameter of *63.7 mm* and on the bottom region it has *61.6 mm*. Simulations with the symmetric longitudinal position of the ring with the helix coil (Figure 2, 4 and 5) do not show the uneven deformation, and it is not significantly visible for the *10 mm* ring height. Therefore the uneven deformation must be caused by some other source, and a longitudinally non concentric relative location of ring and coil is investigated here. In this simulation, the ring was positioned 1 mm lower along the longitudinal distance and thus it was no longer concentric to the helix coil. The other conditions were maintained as the same as the *10 mm* ring expansion test case. The simulation result (Figure 6b) clearly shows a good agreement with the experimental result in terms of its final dimensions and its final shape of the ring. The outer diameters on the top and bottom regions of the ring are predicted as *63.6 mm* and *62.4 mm* respectively. The comparison shows that the uneven deformations between the top and bottom are resulted from the relative position of the ring.

5 CONCLUSION

This paper shows an investigation of inhomogeneous deformation that occurs during the electromagnetic ring expansion tests. Experimental test cases clearly show the out of plane deformation for the case of rings with *5 mm* height and uneven deformations for the cases of rings with *10 mm* height. Numerical simulations are used to identify the underlying phenomena of this inhomogeneous deformation during the coupled problem and to completely eliminate or minimize the effect of inhomogeneous deformation that occurs during the ring expansion test. A rigid body rotation was identified as one of the reason for this heterogeneous deformation, and it was caused by the asymmetric distribution of Lorentz force. Relative position of the ring to the helix coil (i.e. non concentric dislocation of ring and coil) is also identified as another reason for these inhomogeneous deformations. However, in order to quantitatively evaluate their individual influences, more tests are required with various ring heights or coil lengths, and with different input energies. Besides, certain techniques such as high speed camera or multi-point PDV can be used to record the deformation and to capture the rigid body movements of rings. Moreover, in order to avoid inhomogeneous deformations, the coil may be fabricated as symmetric part and the ring should be located at the center of the coil to avoid unnecessary expansion behavior of the ring.

REFERENCES

[1] L. Meyer, Material behaviour at high strain rates, in *1st International Conference on High Speed Forming*, Dortmund, (2004), pp. 45-56.

[2] F. I. Niordson, A unit for testing materials at high strain rates, *Experimental Mechanics,* (1965) vol. 5, pp. 29-32.

[3] D. Grady and D. Benson, Fragmentation of metal rings by electromagnetic loading, *Experimental Mechanics,* (1983) vol. 23, pp. 393-400.

[4] M. Altynova, X. Hu, and G. S. Daehn, Increased ductility in high velocity electromagnetic ring expansion, *Metallurgical and Materials Transactions A,* (1996) vol. 27, pp. 1837-1844.

[5] J. Imbert, T. Rahmaan, and M. Worswick, Interrupted pulse electromagnetic expanding ring test for sheet metal, in *EPJ Web of Conferences*, (2015), p. 01048.

[6] J. R. Johnson, G. Taber, A. Vivek, Y. Zhang, S. Golowin, K. Banik, *et al.*, Coupling Experiment and Simulation in Electromagnetic Forming Using Photon Doppler Velocimetry, *Steel Res. Int.,* (2009) vol. 80, pp. 359-365.

[7] K. Yang, G. Taber, T. Sapanathan, A. Vivek, G. Daehn, R. Raoelison, *et al.*, Suitability of the electromagnetic ring expansion test to characterize materials under high strain rate deformation, in *NUMIFORM, 12th international conference on Numerical Methods in Industrial Forming Processes*, Troyes, (2016).

[8] D. A. Ward and J. L. T. Exon, Using Rogowski coils for transient current measurements, *Engineering science and education journal,* (1993) vol. 2, pp. 105-113.

[9] *LS-DYNA Keyword User's Manual R8.0*. Livermore, CA, USA: Livermore Software Technology Corporation (LSTC), (2015).

[10] P.L'Eplattenier, Introduction of an Electromagnetism Module in LS-DYNA, presented at the Ohio State University workshop on Magnetic Metal Forming, Columbus, OH, USA, (2005).

[11] I. Çaldichoury and P. L'Eplattenier. (2012). *EM Theory Manual*.