Material Constitutive Parameter Identification using an Electromagnetic Ring Expansion Experiment Coupled with LS-DYNA® and LS-OPT®

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Abstract

In this paper, a parameter identification procedure to obtain the constitutive properties of metals at high strain rate and high temperature is presented. This procedure uses experimental results from electromagnetic ring expansions, coupled with LS-DYNA® simulations using the newly developed electromagnetism module, driven by LS-OPT®. The experiments were performed at The Ohio State University and the expansion velocities of the ring were measured. These are used as the target data for the optimization process where the constitutive properties are varied. The procedure is presented in details. It is then tested on a numerical case where the target velocity was generated by a simulation with given constitutive properties. Finally, it is used to find the constitutive properties of a copper alloy.

Introduction

There is very little experimental data on material constitutive properties at high strain rate within a local high temperature environment. Magnetic ring expansion experiments can lead to high strain rate in the order of 10^2 to 10^4 s^{-1} and with temperatures rising up to several hundred degrees [1]. In such experiments, a source current in a coil induces an eddy-current in a metallic surrounding ring. This current, coupled with the induced magnetic field creates electromagnetic forces expanding the ring. The current flowing through the ring also creates an ohmic (or Joule) heating. The Ohio State University (OSU) has the capabilities to perform such experiments for different ring materials and at different energy levels [2]. The velocity of the expanding ring is measured using Photon Doppler Velocimetry (PDV) measurements. The primary current in the coil and the induced current in the ring can also be measured. The new electromagnetism (EM) module recently introduced in LS-DYNA allows simulating these ring expansion experiments, both in 3D and in 2D axisymmetric configurations [3][4]. The experimental current in the coil can be imposed in the simulation. The only unknowns in the simulation are thus the material constitutive properties of the ring, i.e. the stress as a function of the strain, strain rate and temperature, as well as the electromagnetism equation of state, namely the electrical conductivity versus temperature and density. These constitutive properties have a very important influence on the velocity of the expanding ring, hence the idea of trying to get some insight about these properties by numerically reproducing the experimental expansion velocity.

In this paper, a procedure to obtain the constitutive properties of the ring materials is presented. The parameters of a Johnson-Cook (JC) [5] material model were regarded as the constitutive properties. To calibrate the material properties to the experimental data, LS-DYNA® simulations integrated with the optimization capability of LS-OPT® were utilized.

In the first part, a typical magnetic ring expansion experiment is presented. Various simulations for a given ring expansion case using the electromagnetism module of LS-DYNA are then presented. The goal of this phase was to find the fastest running mesh with accurate results. The simulations were applied to both 3D and 2D axi-symmetric configurations. The mesh density was varied in different ways. Simultaneously, the mechanical (velocity), thermal (temperature) and electromagnetic (current density, electromagnetic force, conductivity) fields were investigated in detail.

In the second part, a numerical optimization study is shown. Using a given set of parameters for the Johnson-Cook model, a ring expansion velocity curve was generated as reference data using LS-DYNA. We then started the LS-OPT optimization process using a different set of starting parameters in order to match the reference curve. This phase constitutes the solution of an inverse problem and allowed us to see how closely the optimized parameters could approximate the reference ones. This process was repeated at different energy levels where the ring explores different paths in the (strain, strain rate) plane.

In the third part, we use the afore-mentioned methodology together with the experimental data from the OSU electromagnetic forming group to identify material parameters for the Johnson-Cook model.

Magnetic Ring Expansion

Magnetic ring expansion experiments have been studied in detail in the past, and in particular as a high strain rate test [1]. In a typical magnetic ring expansion experiment, a pulsed power generator discharges into a multi-turn solenoid coil. This source current, which typically rises to a few 10 of kA in a few μs, creates a magnetic field around the coil and an induced current in a metallic ring initially placed around the coil. This creates a radial electromagnetic “Lorentz” force, which expands the ring. The ring expands with velocities of a few tens m/s, depending on the material as well as on its initial radius and cross sections. This generates strains in the order of 1 to 2 and strain rates in the order of 10^2 to 10^4 s^{-1}. The induced current in the ring, typically in the order of a few 10 kA also creates significant Joule heating, with temperatures rising to several hundred degrees Celsius. During the expansion different paths in the (strain, strain rate, temperature) space are explored by the different parts of the ring. A global indicator for these paths is measured experimentally: the ring expansion velocity, i.e. the velocity of the outer radius of the ring versus time. This is this global variable that we try to reproduce numerically by varying the material properties. This is done using the optimization module LS-OPT.

For this part we consider a one turn coil, i.e. a torus with a square cross section (1cm x 1cm) and an inner radius of 13.6 cm. The ring also is a torus with a square cross section (1cm x 1cm) and an inner radius of 15.5 cm. The geometry thus is 2D axi-symmetric. The EM module allows solving the EM fields both in 3D and in 2D axi-symmetric configurations. The evident advantage of 2D simulations is the short computational time. Before starting the optimization process, it is important to find a numerical configuration giving accurate results with a run time as short as possible, since many runs are expected during the optimization process. In order to do so, numerous 3D and 2D axi-symmetric simulations were performed on this case, where the mesh density was varied in different ways. The expansion velocities were compared, as well as the induced current in the ring, and the mechanical (strain), thermal (temperature) and electromagnetic (current density, electromagnetic force, conductivity) fields were investigated in detail.

We now present some comparisons between the following simulations:

- A 2D case with 12x12 elements in the cross sections of both the coil and the ring.
- A 2D case with 24x24 elements in the cross sections of both the coil and the ring.
- A 2D case with 36x36 elements in the cross sections of both the coil and the ring.

Figure 1 shows a comparison between the current densities through the cross section of the ring at a given time during the expansion for the 3 different cases, and figure 2 shows a comparison between the total currents in the coil as well as the ring expansion velocities. Table 1 shows a comparison of simulation times for the 3 different cases, as well as for a full 3D case.

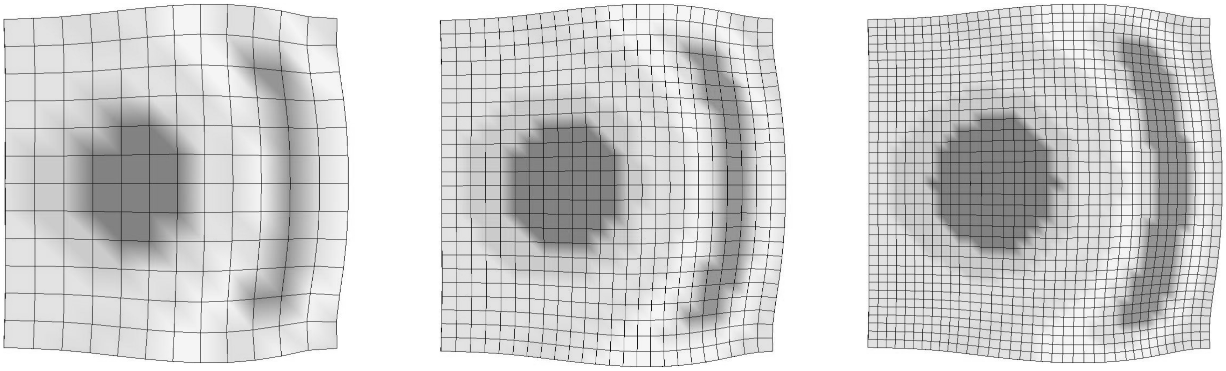

***Figure 1**: comparison of the current density profiles at a given time for the 12x12 element case (left), 24x24 elements (center) and 36x36 elements (right)*

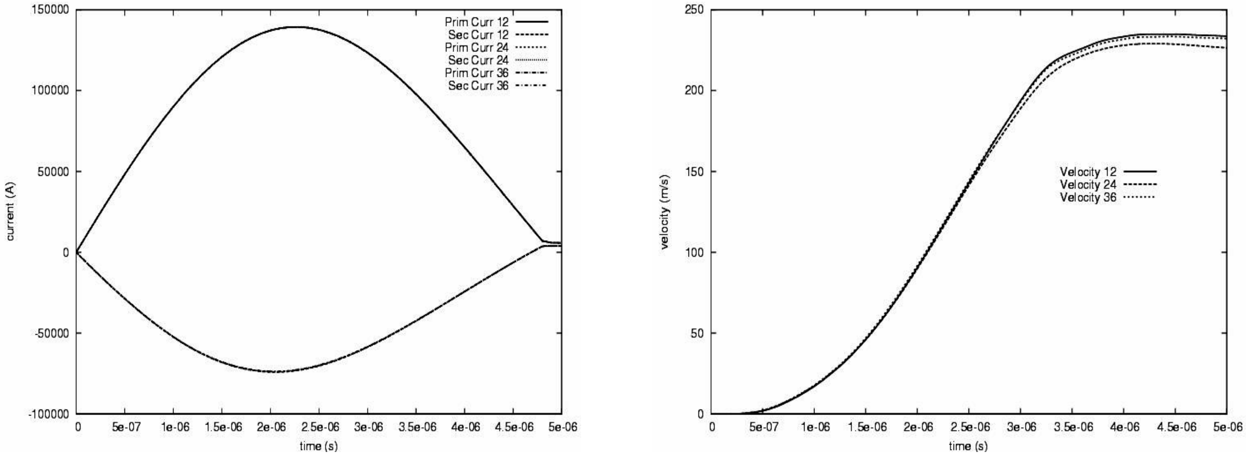

***Figure 2**: comparison of the primary and secondary currents (left) and expansion velocities (right)*

As expected, the thinner meshes show more detail in the current density profiles, but the main characteristics of these profiles are correct even in the coarse 12x12 simulation. Moreover, the global quantities, and in particular the induced current, and the expansion velocities, are very close to each other. These conclusions, along with the big differences in computational time made us choose the 12x12 elements mesh for the following optimizations.

Simulation mesh	Simulation time
Full 3D case 6x6 elements in (r,z) ring	2h 31mn
2D axisymmetric 12x12 elements in (r,z) ring	1mn 26s
2D axisymmetric 24x24 elements in (r,z) ring	1h13mn
2D axisymmetric 36x36 elements in (r,z) ring	2h 1mn

***Table 1**: comparison of the simulation times between the different cases. A full 3D case with 6x6 elements in the cross section was added for comparison.*

Numerical Optimization Study

Good establishment of a model of metal forming experiments depends a lot on a good knowledge of the material properties, and in particular of the stress σ vs. strain ε relationship. For magnetic metal forming, where the forming process occurs in a few tens of microseconds and which involves significant Joule heating, the variation of the stress with the strain rate $\dot{\varepsilon}$ and the temperature T is also very important to consider. Different models for $\sigma(\varepsilon,\dot{\varepsilon},T)$ exist based on microscopic or macroscopic observations such as the Johnson-Cook (JC) [5] , Zerilli-Armstrong (ZA) [6] and Steinberg (S) [7] models. All of these models give an analytical function $\sigma(\varepsilon,\dot{\varepsilon},T)$ which depends on a few parameters, which have to be adjusted for each material used. For example, the JC model, which will be used in the following, writes:

$$\sigma(\varepsilon,\dot{\varepsilon},T) = (A + B\varepsilon^{N})(1 + C\ln\dot{\varepsilon})(1 - T^{*M}) \tag{1}$$

and depends on 5 parameters: A, B, C, N and M. Very little published data exist for the values of these parameters mostly because high strain rate experiments using mechanical forces in a controlled way are difficult to perform. Magnetic ring expansion experiments using magnetic forces represent very well controlled experiments, easy to diagnose, and allowing to explore a wide range of ε, from 0 to 2, $\dot{\varepsilon}$, from 0 to 10000s^{-1}, and T, from 0 to 200°C.

In this part, a numerical optimization study is presented. For this study, we did not take into account the temperature dependency of the Johnson-Cook equation (1), and considered a simplified Johnson-cook model:

$$\sigma(\varepsilon,\dot{\varepsilon}) = (A + B\varepsilon^{N})(1 + C\ln\dot{\varepsilon}) \tag{2}$$

Using a given set A_R, B_R, C_R, N_R of parameters for the Johnson-Cook model, a reference ring expansion velocity curve was generated by running LS-DYNA. We then used LS-OPT to try to match the reference velocity curve, starting from a different set of parameters. This phase allowed us to see how closely the optimized parameters could approximate the reference ones. The quality of a set of parameters (A, B, C, N) is actually not measured by how close it is to the reference set (A_R, B_R, C_R, N_R) but by how close the stress function $\sigma_{A,B,C,N}(\varepsilon,\dot{\varepsilon})$ is to the reference one $\sigma_{A_R,B_R,C_R,N_R}(\varepsilon,\dot{\varepsilon})$ in the domain of interest. We thus not only compared the optimized set of parameters (A_O, B_O, C_O, N_O) with the reference one (A_R, B_R, C_R, N_R), but also looked at the relative error between the reference and the optimized stresses:

$$\Delta\sigma(\varepsilon,\dot{\varepsilon}) = \frac{\left|\sigma_{A_O,B_O,C_O,N_O}(\varepsilon,\dot{\varepsilon}) - \sigma_{A_R,B_R,C_R,N_R}(\varepsilon,\dot{\varepsilon})\right|}{\sqrt{\sigma_{A_O,B_O,C_O,N_O}(\varepsilon,\dot{\varepsilon})\sigma_{A_R,B_R,C_R,N_R}(\varepsilon,\dot{\varepsilon})}} \tag{3}$$

In particular, we compared the iso-contours of $\Delta\sigma$ with the path taken by the ring in the $(\varepsilon,\dot{\varepsilon})$ space. This is shown on figure 4, and table 2 compares the reference parameters with the optimized ones. We can see that even if there are significant differences between the reference and optimized parameters, the relative difference $\Delta\sigma$ stays under 3 % in most of the domain of interest, i.e. for $0 \le \varepsilon \le 1$ and $0 \le \dot{\varepsilon} \le 12000 s^{-1}$. Figure 3 shows the quality of the optimization process by a comparison between the target (reference) and optimized velocity profiles.

We then decided to look if we could improve the accuracy of the optimized parameters when doing the previous process on several ring expansion experiments at different energies, using the same ring material. These different experiments allow exploring a larger part of the $(\varepsilon,\dot{\varepsilon})$ space and we hope the resulting optimization will give a better set of parameters. We now show the result of such a process at 3 energies. Note that the first energy corresponds to the case presented previously. The comparison between the reference and optimized parameters is also shown in table 2. Figure 5 shows the relative error $\Delta\sigma$ for the stress between the reference and optimized parameters in the $(\varepsilon,\dot{\varepsilon})$ space with the paths taken by the ring in this space during its expansions for each of the 3 energies. We can see that not only the Johnson-Cook parameters are closer to the reference ones than in the case with only 1 energy level, but also that $\Delta\sigma$ now stays below a 1% relative error in most of the $0 \le \varepsilon \le 1$ and $0 \le \dot{\varepsilon} \le 12000 s^{-1}$ domain.

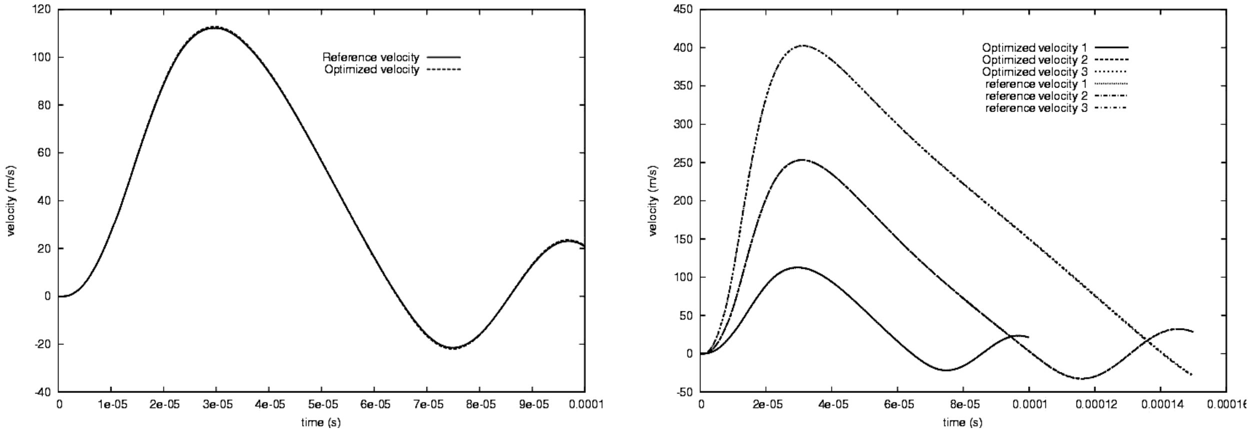

***Figure 3**: comparison between the target (reference) and optimized velocity profiles for the case at 1 energy (left) and the case at 3 different energies (right)*

Johnson-Cook Parameter	Optimization 1 energy level	Optimization 3 energy levels	Reference
A (MPa)	101.2	160.5	170
B (MPa)	500	444.7	423
N	0.3	0.389	0.42
C	0.0269	0.02915	0.0335

***Table 2**: comparison between the reference Johnson-cook parameters and the optimized ones for the optimization using 1 energy level case and the optimization using 3 energy levels cases.*

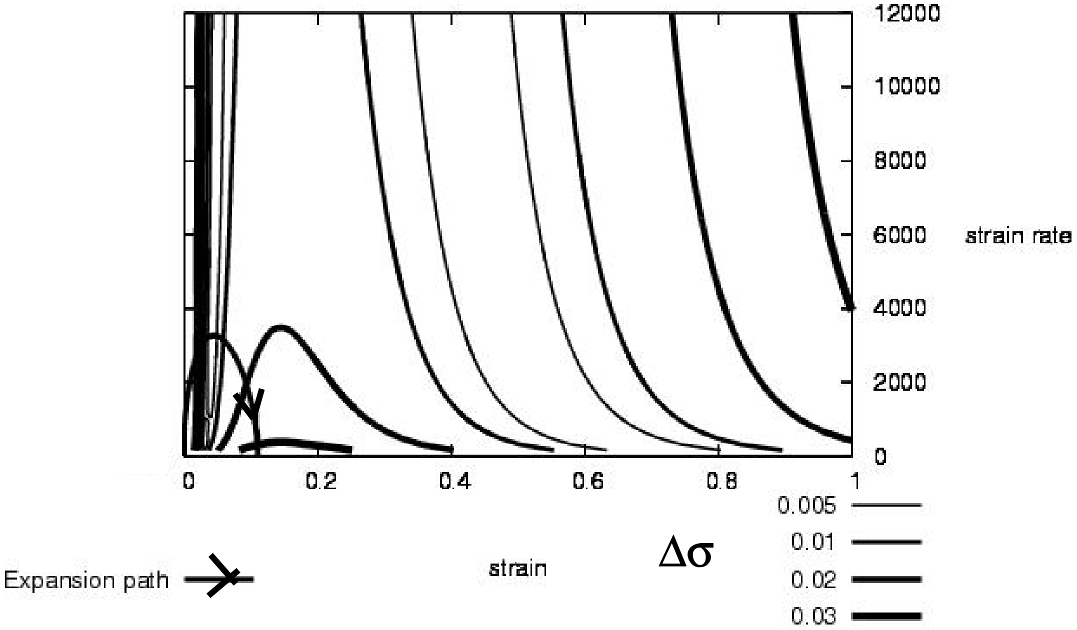

***Figure 4**: isovalues of $\Delta\sigma$ (see equation 3) in the strain, strain rate (in s^{-1}) plane as well as path taken by the ring during its expansion.*

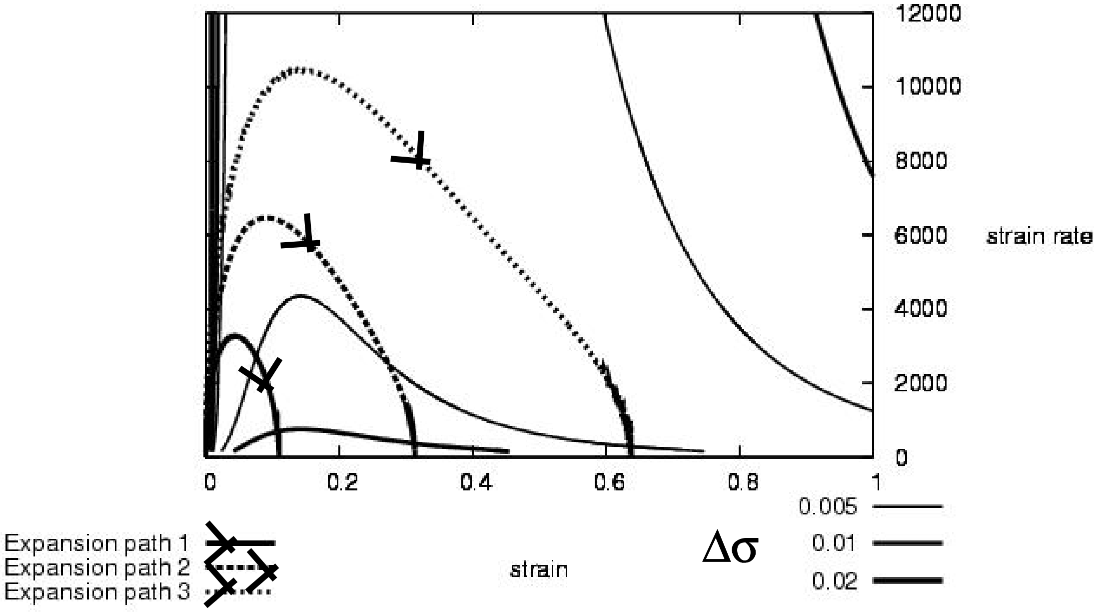

***Figure 5**: isovalues of $\Delta\sigma$ (see equation 3) in the strain, strain rate (in s^{-1}) plane as well as paths taken by the ring during its expansions at each of the 3 energies.*

Parameter identification from an actual ring expansion experiment

In this part, we present the afore-mentioned methodology on an actual experiment. performed at The Ohio State University. This experiment was an electromagnetic expansion of a 31mm long, 62mm inner diameter, 62.5mm outer diameter general purpose copper (Alloy 122) tube at 1kJ energy level. The coil was a 5 turns coil with a 5.93cm outer diameter, a 4.7mm x 4.7mm square cross section, and a 6mm pitch. The primary (coil) and secondary (ring) current waveforms were measured using Rogowski probes, and the ring expansion velocity was measured using a PDV.

The simulations were done in 2D axisymmetric configuration, with 12 x 12 elements in the cross section of each turn of the coil. The ring had 120 elements (height) x 5 elements (thickness). LS-OPT was then used to match the experimental velocity on a JC model (1).

Figure (6) shows the coil and the ring at initial time and at final time for the simulation with the optimized Johnson-Cook parameters. Table (3) shows the final value of the JC parameters, and figure (7) a comparison between the experimental velocity and the numerical one after the parameter identification process. One can see that even if the general shape of the experimental velocity profile is reproduced numerically with the optimized parameters, there still are discrepancies when looking at the details. The very elongated shape of the tube may require a thinner mesh than the one used. Further such parameter identification processes will be performed on cases with less elongated tubes and a more 1-D behavior. This will allow simpler meshes, faster simulations and the introduction of more parameters in the optimization process. In particular, some parameters describing the electrical conductivity versus temperature in an Equation Of State may also be introduced.

One can also notice the low value of the work hardening exponent N compared to a typical OFHC copper (where N=0.31). Such low values of the exponent have been found for cold-worked Cu [8][9].

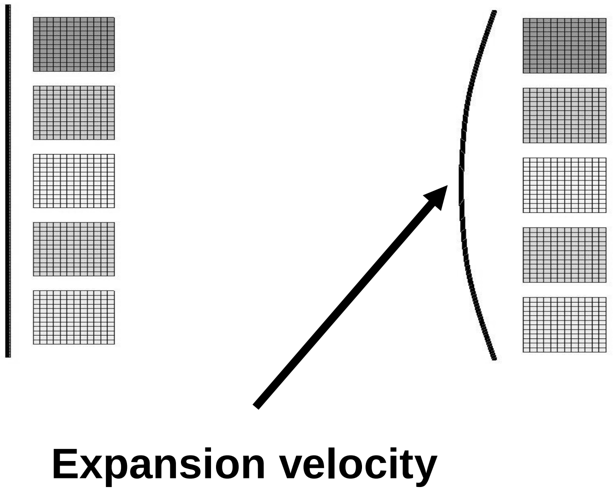

***Figure 6**: cross section of the 5 turns coil and tube at initial time (left) and at final time (right). It also shows the position of the node where the velocity was measured.*

Johnson-Cook parameter	Value after parameter identification
A (MPa)	525.20
B (MPa)	100
N	0.1
C	0.044
M	2.83

***Table 3**: Values of the Johnson-Cook parameters for general purpose copper (alloy 122) after parameter identification.*

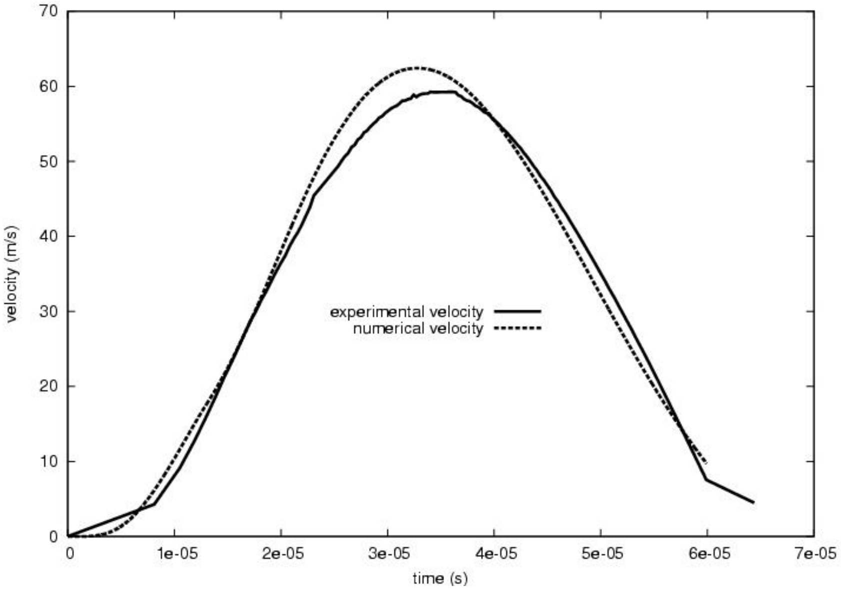

***Figure 7**: Experimental (solid line) and optimized (dotted line) ring velocities vs time*

Conclusion

A parameter identification procedure to obtain the constitutive properties of metals at high strain rate and high temperature was presented. This procedure uses experimental results from electromagnetic ring expansions performed at The Ohio State University, coupled with LS-DYNA simulations using the newly developed electromagnetism module, driven by LS-OPT. A numerical study of this procedure showed that the use of results from several experiments with the same material at different energy levels, spanning a broader part of the (strain, strain rate) space, improved the conditioning of the regression problem, which made the optimization process more efficient and accurate. The procedure was then illustrated on a copper alloy where the Johnson-Cook parameters were identified by reproducing the experimental ring expansion velocity.

The Ohio State University has the capability to easily perform such tests on different materials, at different energy levels and with different ring shapes, with very precise measurements of the currents and expansion velocities. These experimental data will allow us to do more parameter identifications in the future.

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