Experimental Study and Numerical Simulation of Electromagnetic Tube Expansion*

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Abstract

Material constitutive models are important to predict deformation behaviour of materials. To identify parameters of constitutive models for high-strain-rate forming, appropriate methods are needed to investigate the dynamic behaviour of materials. Electromagnetic forming is a high-velocity and high-strain-rate forming process in which velocities of up to 300 m/s and strain rates of more than 10^3 s^{-1} can be achieved. Recently, the development of Photon Doppler Velocimetry (PDV) enables the accurate measurement of high velocity, and the electromagnetism module of LS-DYNA allows the reliable simulation of electromagnetic forming. In this study, PDV and LS-DYNA were applied to investigate the electromagnetic tube expansion of Al 6061-T6. The experimental and simulation results are presented and discussed to study the dynamic behaviour of Al 6061-T6 and to verify constitutive model parameters for it.

Keywords

Forming, Simulation, Modelling

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1 Introduction

Material constitutive models are used to describe the mechanical behaviour by mathematical formulation of the relationship between strain, stress and other variables. Suitable constitutive models with proper parameters are critical to perform numerical analysis and to predict material deformation. For high-strain-rate deformation, constitutive models should include the term to describe the effect of strain rate. There are several techniques to obtain the experimental data on constitutive properties at high strain rate, such as dropweight machines, split Hopkinson pressure bars, Taylor impact and shock loading by plate impact [1]. In 1965, Niordson [2] pioneered the experimental investigation of high strain rate tests with electromagnetically driven ring expansion. In the 1980s, Gourdin [3] extended the capability of electromagnetically driven ring expansion by using Velocity Interferometer Systems for Any Reflector (VISARs) to measure the ring expansion velocity. Velocity measurement coupled with theoretical models allowed for the deformation behavior to be studied at high strain rates in ring expansion experiments. This test was also used to investigate ductility and fragmentation at high strain rates [4, 5]. But VISARs are difficult to use routinely for velocity measurements and therefore this test was not widely used. Recently, Daehn [6] proposed to apply electromagnetically driven ring expansion for determination of the high-strain-rate constitutive properties with the help of the cutting edge technology, Photon Doppler Velocimetry (PDV), which has the capability to accurately measure the ring expansion velocity and also is easy to apply. Johnson [7] furthered the development with Fully Instrumented Ring Expansion (FIRE) system with electromagnetic actuator and exploding wire actuator.

Moreover, an electromagnetism (EM) module has been developed by LSTC for the numerical simulation of electromagnetic forming [8]. In this module, the electric current going through the actuator (coil) can be set as the input and then the workpiece deformation (such as strain, strain rate, stress, velocity…) can be calculated if the material properties are known. In the case of electromagnetic ring expansion, the ring expansion velocity can be measured using PDV and the electric current can be measured using a Rogowski coil. Therefore, EM module can be applied to calculate the expansion velocity with the measured current as input, and the predicted expansion velocity can be compared to the measured velocity, which will help identify constitutive models used in the finite element simulation. Henchi [9] proposed to apply LS-OPT to determine the constitutive properties by optimizing the parameters of Johnson-Cook model with the combination of EM simulation and PDV measurements.

In this paper, a typical EM expansion experiment with Al6061-T6 tube is presented. Then the simulation results using the EM module with several constitutive models of Al6061-T6 are presented and compared to the velocity measurements. The better agreement between the numerical results and the experiment results should indicate the more appropriate constitutive model. In this way, the proper parameters for the Johnson-Cook constitutive models of Al6061-T6 can be verified.

2 Experiment Setup and Results

Figure 1 shows the schematic layout of the EM tube expansion experiment. The capacitor bank used in this experiment was a 16kJ Magneform machine with the maximum charging voltage of 8.66kV, a total capacitance of 426μF and an internal inductance of around 100nH. A 3-turn coil was connected to the capacitor bank to generate electromagnetic forces to expand the tube outwards. The coil was made of Cu with 61mm outer diameter, 6.3mm x 6.3mm square cross section and a 3.6mm pitch. The Al6061-T6 tubes used here have 63.5mm outer diameter, 0.89mm wall thickness and 45mm length.

During the EM tube expansion tests, two PDV probes were applied to measure the expansion velocities, shown in Figure 1. Probe A aimed at the middle of the 3-turn coil, which was to capture the maximum expansion velocity. Probe B was 10mm away from Probe A, which was to get more velocity data for study. The measurement principles of PDV can be found in other papers [6, 7]. Moreover, a Rogowski coil was applied to measure the electric current going through the 3-turn coil during EM tube expansion tests.

Figure 2 is the measured current trace and velocities in the case of 0.8kJ Al6061-T6 tube expansion (the charging voltage is 1.93 kV). The measurements show that the electric current in the 3-turn coil reached the peak value of 63.5kA at 18.0 μs. At the position corresponding to Probe A, the Al tube was accelerated to the peak velocity of 72.7m/s within 24.5μs and then decelerated to the velocity of 4.7m/s at 51.5μs. After that, the Al tube began to vibrate and decay to become stationary.

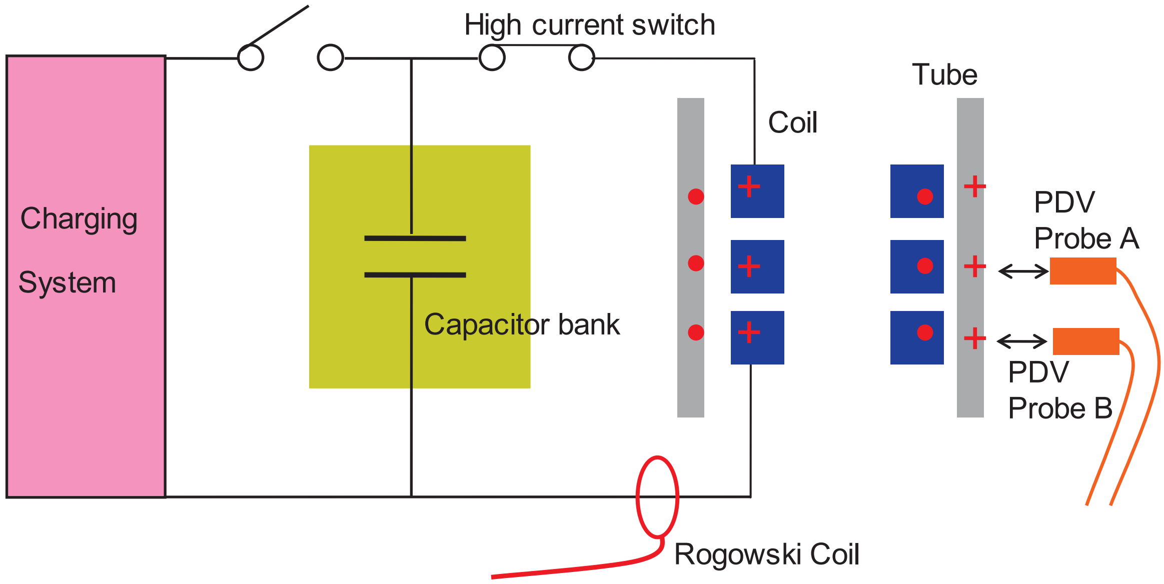

***Figure 1**: Schematic layout of EM tube expansion experiments*

3 Numerical Simulation

3.1 Model

The numerical simulation was performed using the EM module available in the “beta” 980 version of LS-DYNA. In this module, Finite Element Method (FEM) is coupled with Boundary Element Method (BEM) to compute magnetic field, electric field and induced current by solving Maxwell equations in eddy-current approximation. FEM is applied to solve Maxwell equations for the solid conductors and BEM is used for the surrounding air. The detailed introduction of this module can be found in [8].

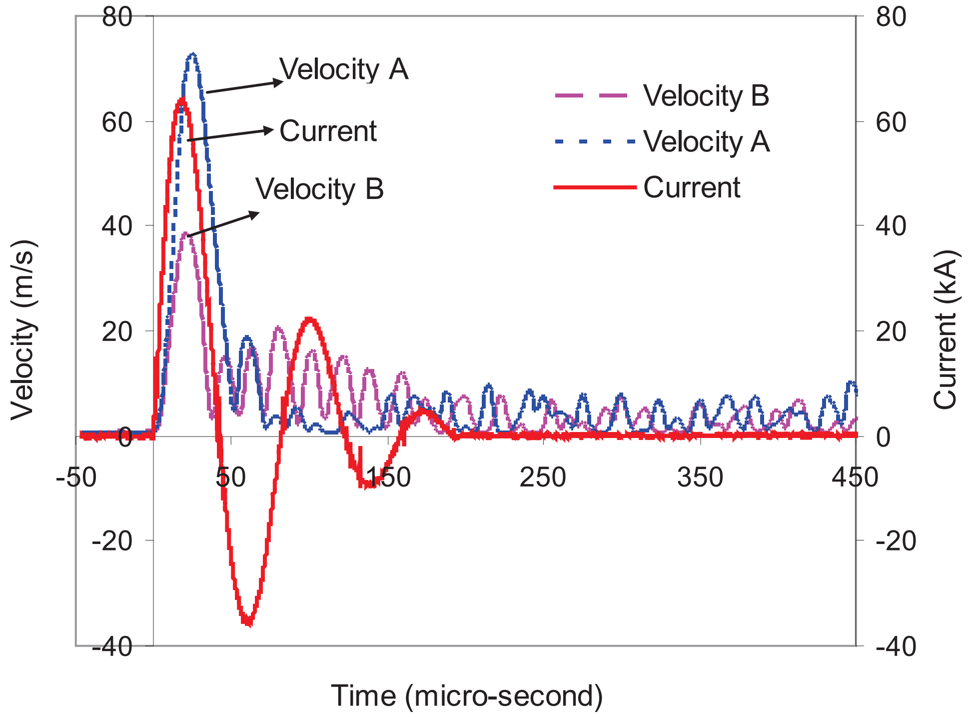

***Figure 2**: Measured current trace and velocities for 0.8 kJ Al 6061-T6 tube expansion*

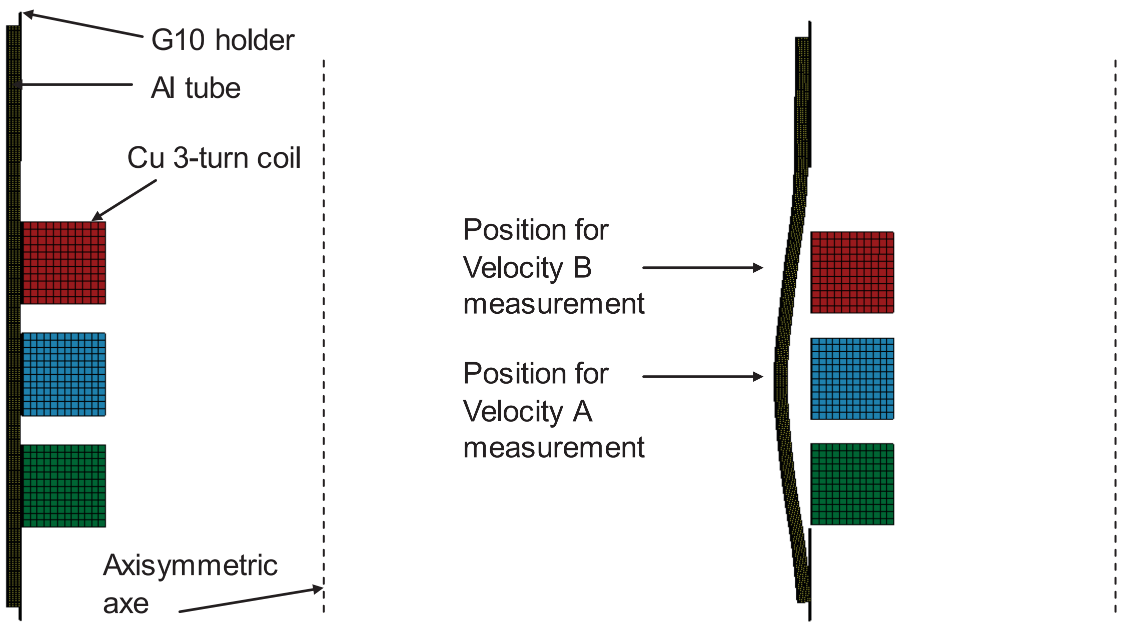

***Figure 3**: 2D axisymmetric model of the 3-turn Cu coil, Al 6061-T6 tube and G10 holder at initial time (left) and at the end of simulation (right)*

A 2D axisymmetric model was built for the numerical simulation, shown in Figure 3. Figure 3 also shows the positions where the velocities were measured. There are three parts: the 3-turn Cu coil, the Al6061-T6 tube and the G10 holder. The 3-turn Cu coil and the Al tube were meshed using eight-node hexagonal solid elements, which are required for the solid conductors in EM module. The G10 holder was meshed with shell elements since G10 Garolite is non-conductive material.

The G10 holder was modelled as a rigid body since it did not have plastic deformation. The 3-turn Cu coil was modelled as elastic material because it did not have plastic deformation during the 0.8kJ EM tube expansion. But for the Al6061-T6 tube, high strain rates and large deformations were involved. Therefore, the Al6061-T6 tube was modelled using the Johnson-Cook strength model, which has the following form [10]:

$$\sigma = (A + B\varepsilon^n)(1 + C\ln\dot{\varepsilon})[1 - (\frac{T - T_{room}}{T_m - T_{room}})^m] \quad (1)$$

where A is yield stress, B is hardening constant, C is strain rate sensitivity, n is hardening exponent, m is thermal softening exponent and Tm is melting temperature. From the literature, four parameter sets of Johnson-Cook strength model for Al6061-T6 were found and listed in Table 1. For each set of parameters, an EM simulation for the case of 0.8 kJ Al6061-T6 tube expansion were performed.

	A (MPa)	B (MPa)	C	n	m	T_m (K)
Model 1 [11]	324	114	0.002	0.42	1.34	925
Model 2 [12]	275	500	0.02	0.3	1.0	925
Model 3 [13]	293	121.3	0.002	0.23	1.34	925
Model 4 [14]	289.6	203.4	0.011	0.35	1.34	925

***Table 1**: Parameters of Johnson-Cook strength model for Al6061-T6*

3.2 Simulation results and comparison

Figure 4 and Figure 5 show the experimental and numerical simulation results of Velocity A and Velocity B respectively. From two figures, it can be seen that the simulations using Model 2 and Model 4 have large difference from the measurements. But the simulations using Model 1 and Model 3 agree well with the measurements in both figures. The peak velocity of Velocity A in the measurement has 2.4% difference from the one predicted with Model 3 and 3.5% difference from the one predicted with Model 1. For the case of Velocity B, the measured peak velocity has the same value as the one predicted with Model 3 and 2.0% difference from the one predicted with Model 1.

Figure 6 shows the effective plastic strain rate and the effective plastic strain at the position where Velocity A was measured, according to the numerical simulation using Model 3 for 0.8kJ tube expansion case. The peak effective plastic strain rate was 2170 s^{-1} at 25.0μs when the effective plastic strain was 0.022, which is truly a high strain rate. The peak effective plastic strain was 0.06. It should be noted that this experiment applied low energy to expand the Al tube. Much larger expansion velocity and strain rate could be reached if increasing energy or using different set-ups. In this paper, the main purpose was to test the feasibility of using PDV and EM module to verify constitutive models. Therefore, only low energy was applied here.

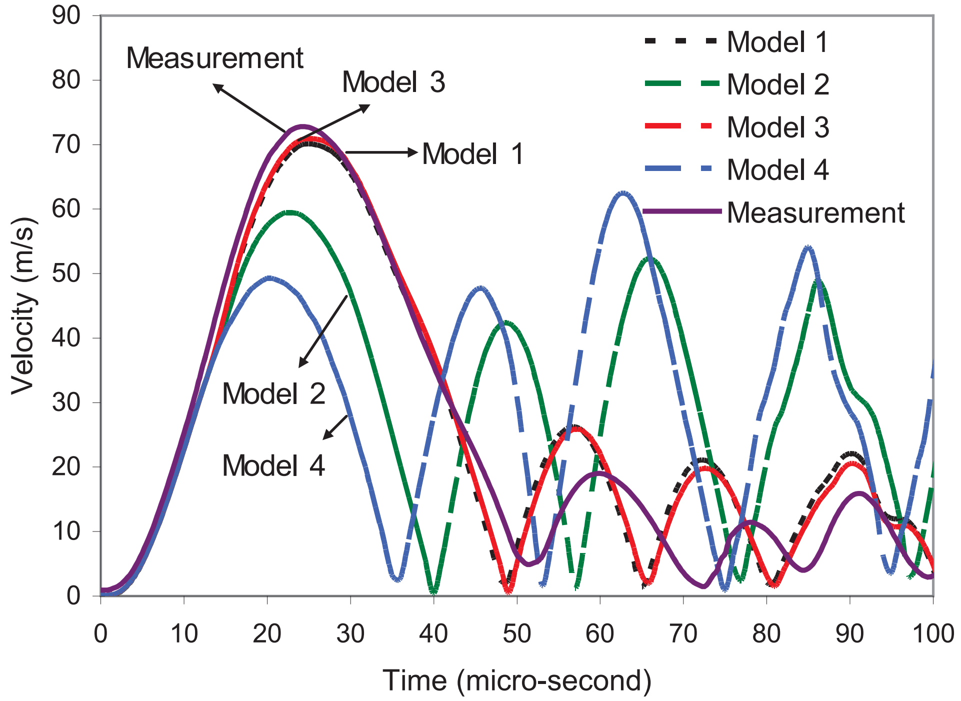

***Figure 4**: Experimental and numerical simulation results of Velocity A*

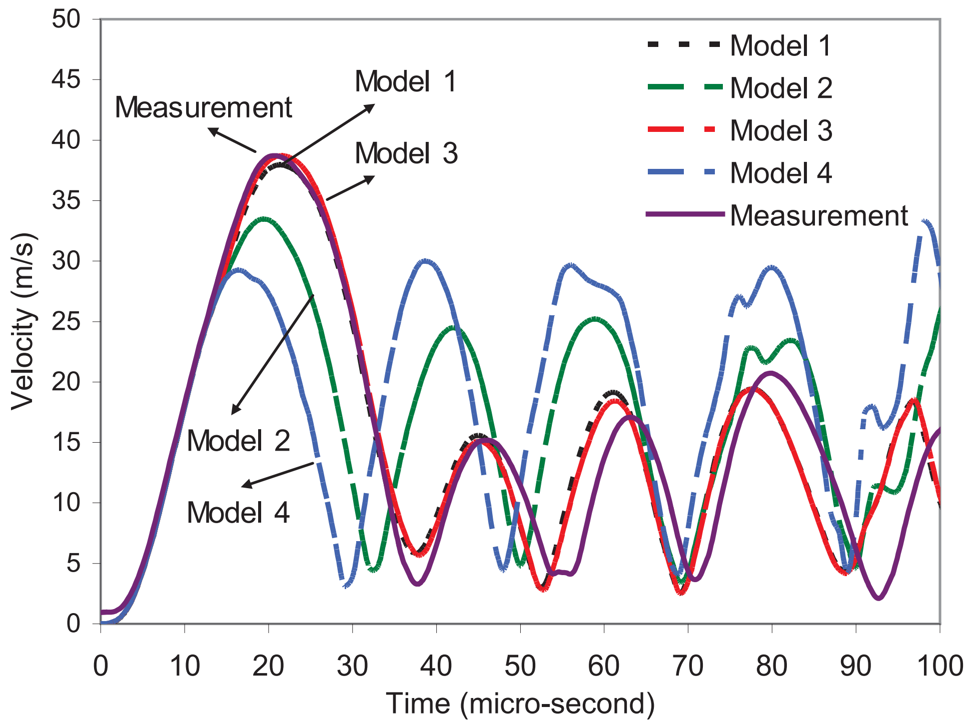

***Figure 5**: Experimental and numerical simulation results of Velocity B*

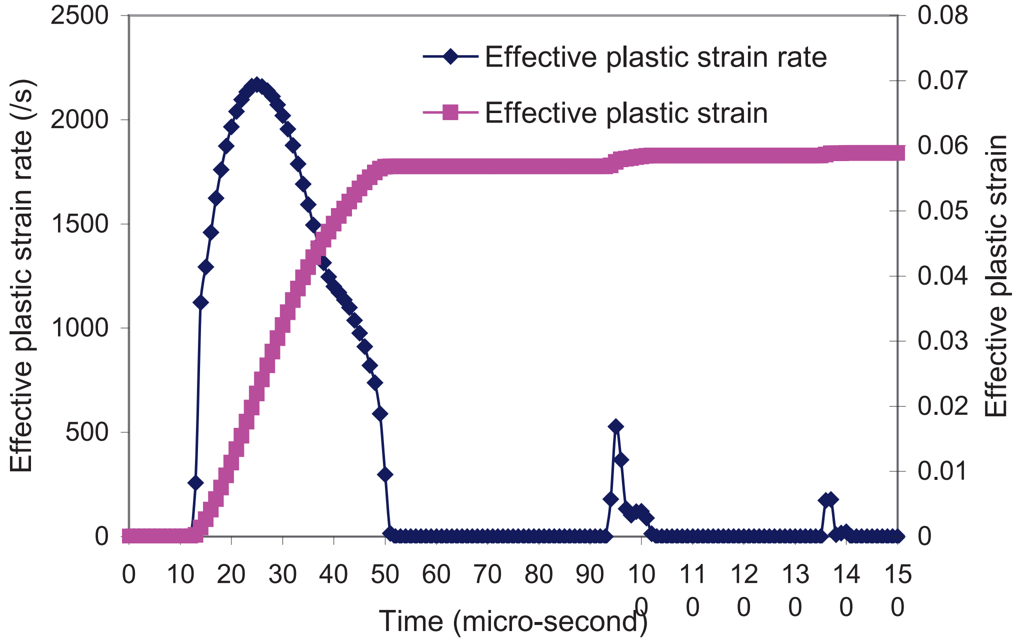

***Figure 6**: Effective plastic strain and strain rate for 0.8 kJ Al 6061-T6 tube expansion*

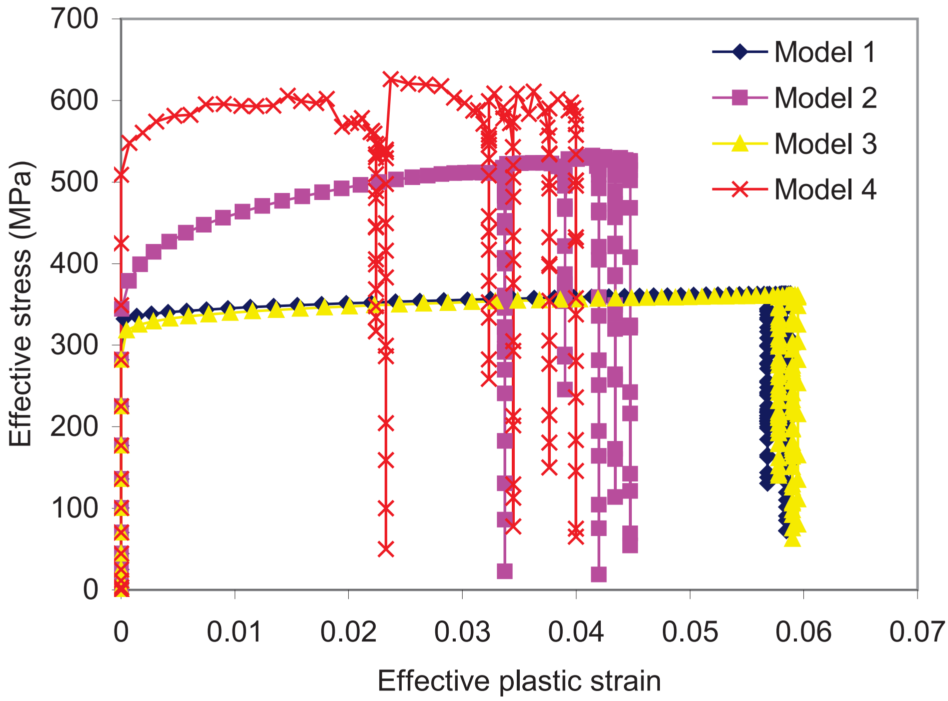

***Figure 7**: Comparison of stress-strain plots during EM forming with different models*

Figure 7 is the comparison of the stress-strain plots in the 0.8kJ EM tube expansion using different models listed in Table 1. It shows that using Model 1 and 3, the effective stress had small increase with the effective plastic strain, which indicated the low strain rate sensitivity. But using Model 2 and 4, the effective stresses were much higher than the ones using Model 1 and 3.

In this study, 2D axisymmetric simulation was used instead of 3D simulation to save computational time. For a spiral coil, there are some simplifications in order to assume 2D axisymmetric case, which may bring in errors. But in this study, 2D axisymmetric simulation results agreed well with the measurement results. Therefore, 2D axisymmetric simulation should be sufficient for the tube expansion with the 3-turn coil in this study.

3.3 Discussion

The comparisons show that the parameters in Model 1 and Model 3 are suitable for Al 6061-T6, but those in Model 2 and Model 4 are not correct. From Table 1, both Model 1 and Model 3 have the same value of the strain rate sensitivity C, which is 0.002. Model 2 and Model 4 have much larger values of the strain rate sensitivity C. Aluminium is traditionally considered to have low strain rate sensitivity. Therefore, the experimental and numerical simulation results in this paper verified this statement, i.e. Al 6061-T6 has low strain rate sensitivity within the range of 0~2170 s^{-1} strain rate.

As it is known, the values of strain rate sensitivity are relative to the strain rates. Researchers [15, 16] have reported that the strain rate sensitivity increases at strain rates above 1000 s^{-1} for aluminium and aluminium alloys. In this study, the peak strain rate was 2170 s^{-1} and the strain rate sensitivity was small for Al6061-T6. It is possible that the strain rate sensitivity of Al6061-T6 will increase if the strain rate is larger than 2170 s^{-1}, such as 10,000 s^{-1}. More experiments are needed to test this statement.

Moreover, the value of hardening exponent n in Model 1 is almost twice of that in Model 3. But both Models predicted the expansion velocities that agreed well with the measurements. So the strain rate hardening has much larger effects than strain hardening in EM Al tube expansion due to high strain rate.

Although the work in this study verified the low value of the strain rate sensitivity for Al6061-T6, the exact value could not be determined only using EM tube expansion tests and numerical simulation by LS-DYNA EM module. Henchi [9] applied LS-OPT to optimize the parameters of Johnson-Cook strength model by several experiments of same material at different energy levels. This could be the way to determine the constitutive properties without utilizing other experimental techniques.

4 Conclusion

Both experiments and numerical simulation of EM Al6061-T6 tube expansion were performed. The PDV technique provides accurate measurements of expansion velocities. The comparisons between EM tube expansion simulation and PDV measurements show the excellent capability of LS-DYNA EM module for EM forming simulation. The combination of PDV and EM module simulation can be applied to verify the parameters of constitutive models in high strain rate and is beneficial for the study of the dynamic behaviour at high strain rates.

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