metals

Article

Numerical Modeling and Experimental Verification for High-Speed Forming of Al5052 with Single Current Pulse

Hyeong-Gyu Park, Beom-Soo Kang and Jeong Kim *

Department of Aerospace Engineering, Pusan National University, Geumjeong-gu, Busan 609-735, Korea; phk9492@gmail.com (H.-G.P.); bskang@pusan.ac.kr (B.-S.K.)
* Correspondence: greatkj@pusan.ac.kr; Tel.: +82-51-510-2477

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Abstract: Application of electric current pulses during plastic deformation changes the mechanical behavior owing to the electro-plastic effect. The effect of electric current pulses on the Al5052 alloy is investigated in this study. In order to demonstrate the advantages of passing electric current pulses through a metal sheet during the forming process, a uniaxial tensile test with an electric current pulse was carried out using a self-designed device; this device can apply a 2-kA electric current pulse to the specimen for a short period (>100ms). The electric current increases the temperature of the specimen due to Joule heating. It is, therefore, necessary to decouple the thermal effect from the overall behavior to understand only the contribution of electric current in the mechanical behavior. Firstly, an electro-thermo-mechanical finite element study of an electrically assisted uniaxial tensile test of Al5052 alloy is performed to isolate the thermal effect. The simulated results yielded the thermal effect due to the electric current. By comparing the experimental and simulated results, the contribution of electric current is decoupled from that of thermal effect. The electric current-dependent material model is implemented into the commercial FEM code LS-DYNA using user-defined material(UMAT) subroutine. The electric current-dependent material model was used to simulate the electro-mechanical finite element analysis of the high-speed forming of an aluminum sheet with electric current pulse. Simulation results were compared with experimental results at several applied electric currents to evaluate the accuracy of the UMAT. The present work can be utilized to develop simpler constitutive models for the mechanical behavior of metals subjected to a pulsed electric current.

Keywords: electro-plastic effect; electric current pulse; tensile test with electric current; Al5052 sheet; FEM; UMAT in LS-DYNA

1. Introduction

Recently, the demand for high strength steels and aluminum alloys is increasing in the automotive industry to improve the efficiency of the fuel and performance. However, these materials pose difficulties in industrial utilization because of their limited formability, e.g., increase in forming load, reduction in die life and occurrence of spring back after the forming process, in an environment of typical room temperature. Therefore, it is popular as hot stamping, forming at an elevated temperature can improve formability (e.g., decrease in forming load and removal of spring back). However, the hot stamping process has disadvantages owing to high temperature, e.g., adhesion between the forming die and material, difficulty in lubrication, time delay for cooling, and requirement of facilities similar to those for a heating furnace. Thus, an improved forming process for aluminum alloys and ultra-high strength steels is required.

The electro-plastic effect is a phenomenon that instantaneously reduces flow stress when an electric current is applied to a material during plastic deformation of the material. The electrically assisted forming, which combines the electro-plastic effect with a general forming process, has attracted attention as a process for improving the formability by decreasing the forming load by using the momentarily reduced flow stress. In fact, extensive research has been conducted on the electro-plastic effect in wire drawing [1–3], compression [4], rolling [5,6], bending [7,8], blanking [9], etc. Andrawes et al. [10] reported that electric current reduced the deformation energy of various metals such as aluminum and copper-based alloys, without substantially increasing the work piece temperature. Fan et al. [11] investigated the influence of grain size and grain boundaries on the thermal and mechanical behavior of 70/30 brass under tension tests with continuous DC current. Breda et al. [12] observed an Influence of stacking fault energy(SFE) in electrically assisted uniaxial tension. Ruszkiewicz et al. [13] proposed the constitutive equation of the continuum theory of sintering to include the electric current effect term. However, a few other studies considered electro-plastic effect as a thermally dominated effect. Conrad [14] suggested that electric current in metals affects only the thermal component of flow stress and not the rate controlling mechanism. There have been many researchers' work, but so far, the mechanism of the electro-plastic effect on plastic deformation remain still unclear, and some researchers are still arguing about the existence of a pure electro-plastic effect. Therefore, in this study, the constitutive equation that can take into account electro-plastic effect and the relationship between electro-plastic effect and temperature were investigated by tensile test and numerical analysis with electric current pulse in aluminum sheet. In the numerical analysis, user-defined material (UMAT) subroutine was used to implement the flow stress that is suddenly reduced by the electric current. Because of the stress drop to take place during a very short period of time, it is also required a special forming process to deform the material within that time. In this work, a high-speed forming process as one of several special forming methods was adopted and a numerical simulation for prediction of deformation behavior of Al5052 sheet under the single current pulse was conducted using an explicit FEM code LS-DYNA combined with UMAT subroutine.

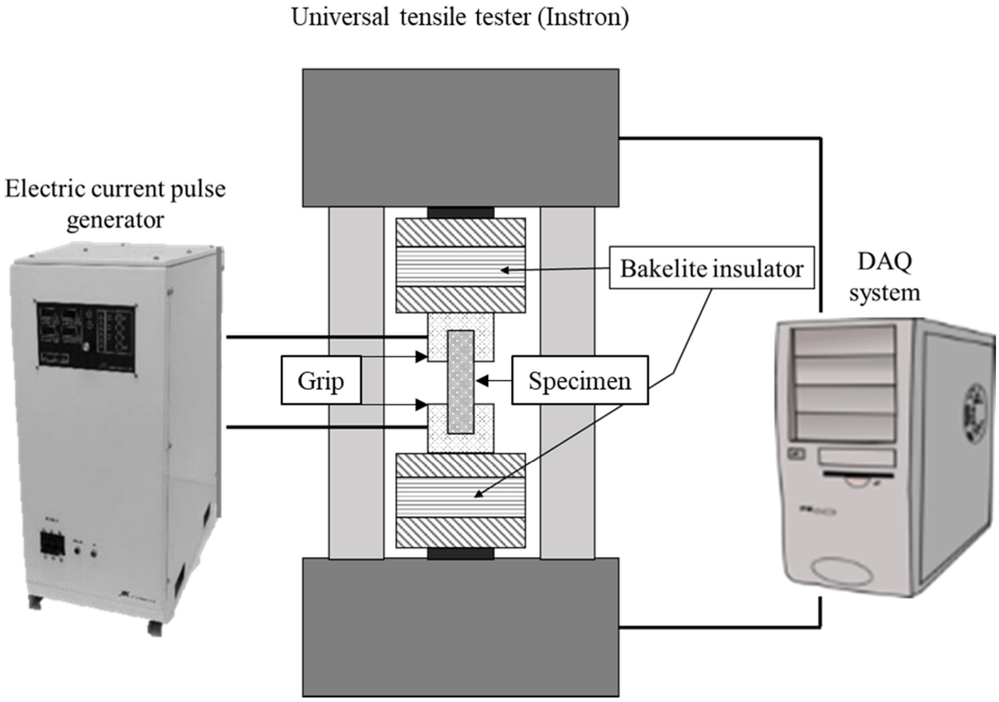
2. Uniaxial Tension Test with Electric Current Pulse

2.1. Experimental Conditions

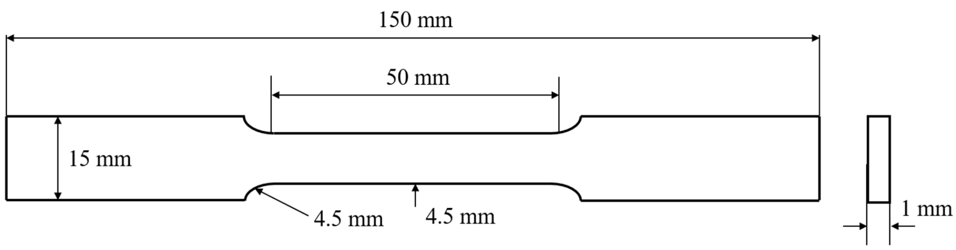
Firstly, the uniaxial tensile test using the current pulse was carried out on the Al5052 alloy sheet. The chemical compositions of the Al5052 alloy are given in Table 1. In order to apply the current pulse to the material during the tensile deformation of the specimen, a self-designed current generator was connected to a universal tensile tester (Instron, USA), as illustrated in Figure 1a. The electric current pulse was applied to both ends of the specimen clamped by insulated grips. Each specimen was fabricated to 4.5 mm gauge width, and 50 mm gauge length by laser cutting along the rolling direction of the sheet as per ASTM E8, which is parallel to the loading direction as illustrated in Figure 1b [15]. An electric current pulse generator was designed to minimize the Joule heating effect in the specimen during the uniaxial tensile test. The specifications of the electric current pulse generator are as follows: the minimum 100 ms pulse duration time, 20 kHz inverter switching frequency, rising-falling time below 100 ms, and 2 kA maximum current. The generator circuit consists of two parts: the rectifier circuit and the switching control circuit. The rectifier circuit incorporates a bridge rectifier to convert alternating current (AC) supplied by the generator to direct current (DC), which is supplied to the specimen. The intensity of the converted DC pulse is induced in the specimen using a capacitor. The switching control circuit incorporates an insulated-gate bipolar transistor (IGBT), which has high efficiency and fast switching. The actual electric current pulse was measured by Rogowski coil and oscilloscope; it matched with designed specifications (peak current; 2 kA, duration time; 100 ms) as presented in Figure 2.

Table 1. Chemical composition of Al5052 alloy (wt%).

Alloying Element	Mg	Fe	Si	Mg	Cu	Mn	Zn	Al
Al5052	2.2–2.28	0.40	0.25	2.2–2.28	0.10	0.10	0.10	Bal.



(a)



(b)

Figure 1. Experimental setup. (**a**) Schematic of uniaxial tensile test with electric current pulse. (**b**) dimensions of tensile test specimen.

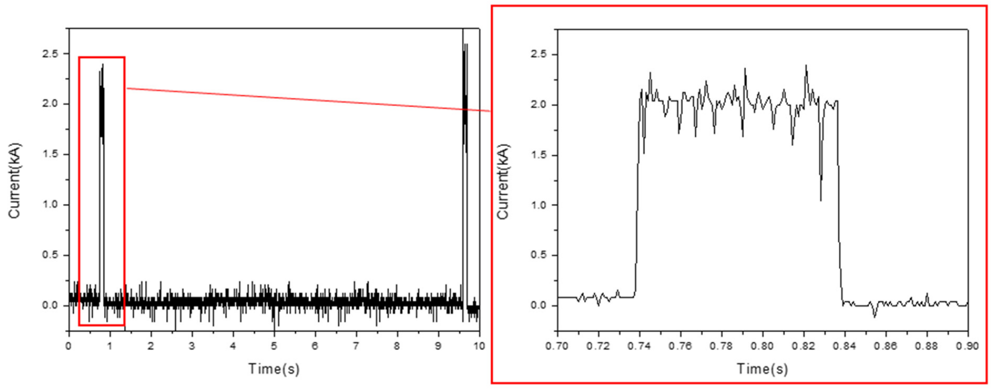


Figure 2. Applied current waveform (peak current; 2 kA, duration time; 100 ms) measured by Rogowski coil.

In the tensile test in which current is applied, the amount of temperature change ΔT that occurs in the specimen during the application of current can be expressed as Equation (1).

$$\Delta T = \frac{Q}{cm} \tag{1}$$

In this case, Q is the heat value, c is the specific heat, m is the mass, and Q can be expressed by the following Equation (2).

$$Q = I^2 Rt \tag{2}$$

where I is the intensity of the current flowing through the material, R is the electrical resistance of the material, and t is the time during which current flows through the material. The following Equation (3) can be obtained by summarizing the Equations (1) and (2).

$$\Delta T = \frac{I^2 Rt}{cm} \tag{3}$$

The change of resistance due to change of temperature was neglected. In this case, since the remaining values except the current intensity and the duration time have the same value in the same specimen, the temperature change amount of the material is determined by the current intensity and the duration time. Therefore, for the tensile test at the same temperature, the current intensity and the duration time are set as shown in the experimental conditions 1, 2, 3, and 4 shown in Table 2. In order to investigate the relationship between the temperature change due to the current intensity and the flow stress reduction with the same duration time, the electric current pulse was applied in the condition of 1, 5, 6 in Table 2. During the tensile test, current was applied to the specimen and the temperature change with time was measured using an infra-red thermal imaging camera.

Table 2. Experimental conditions.

Case No.	**1**	**2**	**3**	**4**	**5**	**6**
Current (A)	1000	707	316	224	707	500
Current density (A/mm^2)	222	157	70	48	157	111
Duration time (s)	0.1	0.2	1	2	0.1	0.1

2.2. Experimental Results

Under quasi-static tensile loads, the flow stress of the selected aluminum alloy significantly decreased nearly instantly when the electric current was applied to the specimen, as shown in Figure 3. The maximum electric current is 1kA and the duration time is 100 ms. The stress–strain curve with black line in Figure 3 is obtained without electric current. This nearly instant decrease in flow stress depicted red line in Figure 3 is defined as a stress drop. Once the electric current was removed from the specimen, the stress of the material rapidly increased and showed strain hardening. When a current is applied to the specimen, the flow stress temporarily decreases and then rises back to the same level as the flow stress without current.

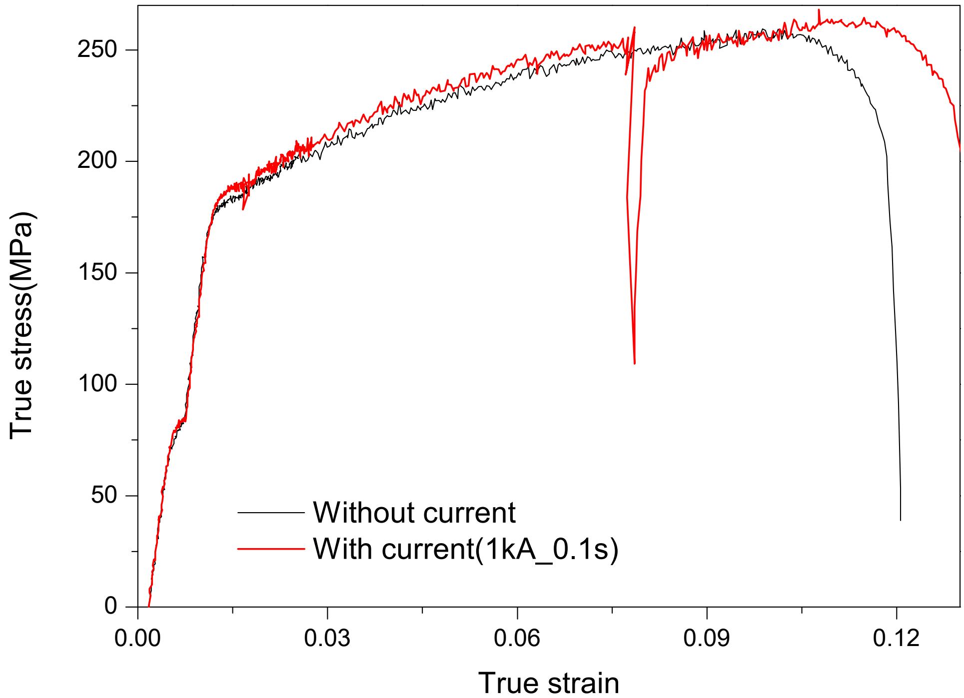


Figure 3. True stress–strain curve of the Al5052 specimen with electric current flow.

The maximum temperatures obtained from the thermal images in Figure 4 suggest that the specimen temperature, even at the moment of electric pulse, was well below the melting temperature (880 K) and within the lower temperature limit required for hot working (533 K). The temperature change due to the applied current was measured during the tensile test as shown in Figure 5. In Figure 5a, all four conditions i.e., case No. 1, 2, 3 and 4 listed in Table 2 show the same temperature change about 150 K. Figure 5b, detailing the temperature rise section, shows that the temperature rises only during the duration time, and that the slope of the temperature change over time is proportional to the square of the current intensity when the current is applied to the specimen. The maximum temperature depending on current intensity during the same duration time is also proportional to the square of the current intensity, as shown in Figure 6. According to Figures 4 and 5a, the temperature rose gradually after the application of the current and then gradually decreased. Since the tension test have no extra cooling time, the tensile test after the flow stress decreases remains at a higher than room temperature (320 K). Nevertheless, it is assumed that the effect of reducing the flow stress due to temperature is very small since the flow stress with electric current recovers to the same level as the flow stress without current as shown in Figure 7. When the current application time is the same as 0.1 s and the current intensity is different, the flow stress is reduced by 150 MPa at 1000 A, 100 MPa at 707 A and 50 MPa at 500 A, and Figure 8 can be seen that the amount of decrease of the flow stress decreases in proportion to the square of the current intensity as in the case of the temperature change amount.

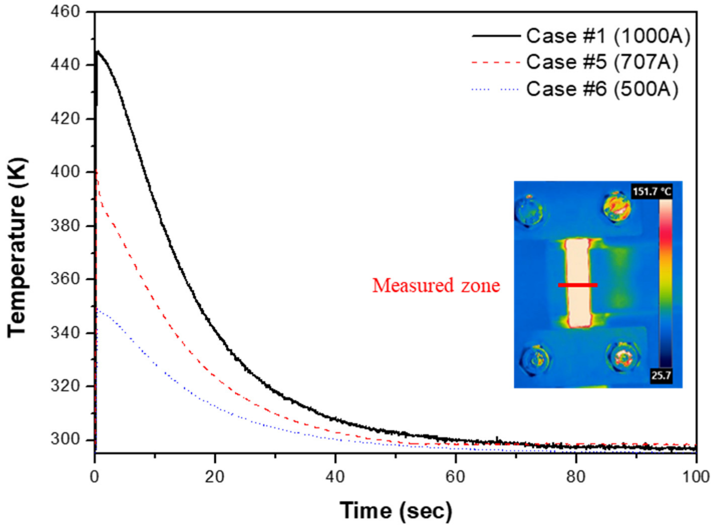
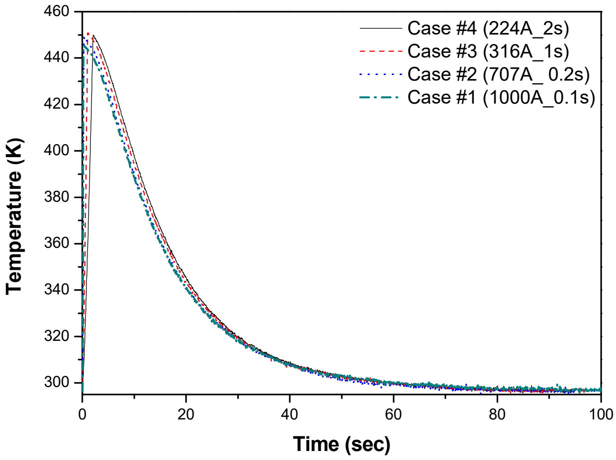
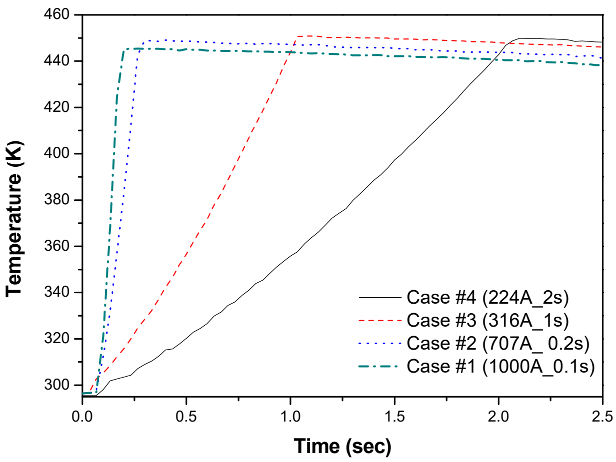


Figure 4. The temperature variations with respect to applied electric current under same duration time 0.1 s.



(**a**)



(**b**)

Figure 5. The measured temperature versus time profile of the specimen under electric current in Al5052 (**a**) until cool down and (**b**) at temperature rising section.

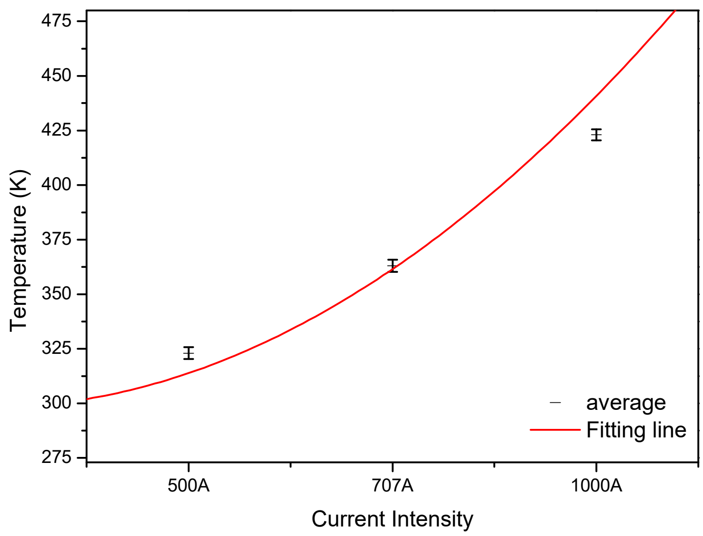


Figure 6. Temperature variation by current intensity during the same current duration time.

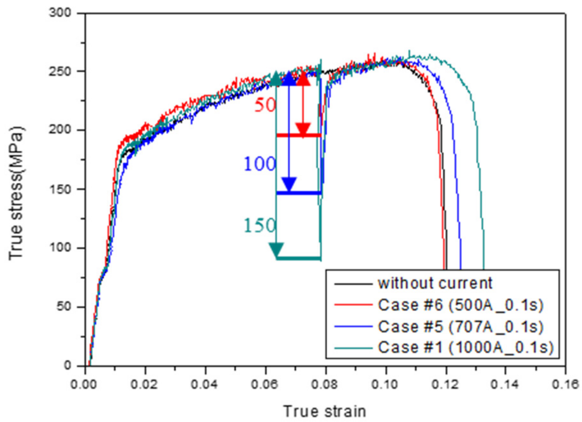


Figure 7. True stress–strain curve of the Al5052 specimen with electric current flow under same duration time of 0.1 s.

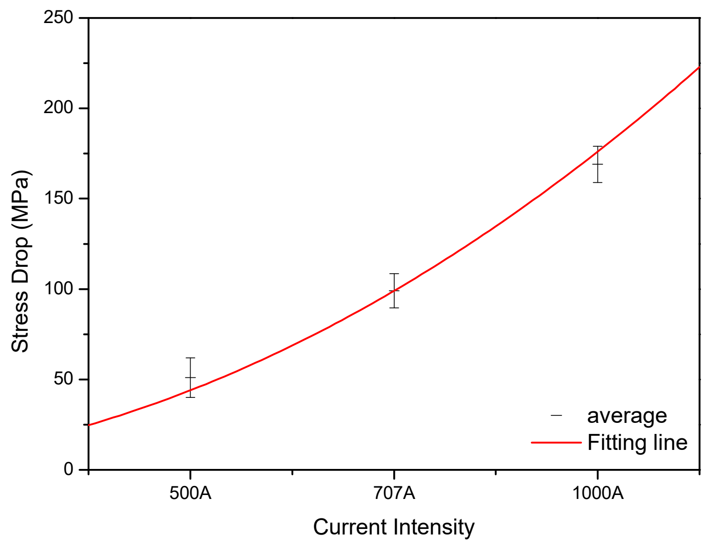


Figure 8. Stress drop by current intensity during the same current duration time.

3. Development and Verification of Constitutive Model

3.1. Constitutive Model Taking into Account Electro-Plastic Effect

Finite element analysis (FEA) was performed using the commercial explicit finite element code LS-Dyna to understand the deformation behavior of the aluminum sheet during the thermo-forming process. The UMAT option was used to build the user material subroutine in FORTRAN, which was then linked with the library files supplied by LSTC.

Flow stress ($\overline{\sigma}$) represents the size of the yield function during deformation. Metals undergoing plastic deformation at high temperatures and different strain rates should be modeled according to the physical behavior of the material (Gronostajski, 2000) [16]. An appropriate constitutive equation describing changes in the flow stress of the material depends on deformation conditions such as temperature. However, the electric current-dependent material model proposed in this study neglects the temperature change due to the application of current and configures the flow stress drop only depending on the current. This paper proposed a flow rule that includes the electro current sensitivity:

$$\overline{\sigma}(\overline{\varepsilon}^p, A) = K(\overline{\varepsilon}^p + \varepsilon_0)^n (1 - \mathrm{B}A^c) \tag{4}$$

where K (strength hardening coefficient), n (strain-hardening exponent), B (electro-plastic effect constant) and c (electric current sensitivity index) are material constants. $\overline{\varepsilon}^p$ is the effective plastic strain and ε_0 is a constant representing the elastic strain to yield and A is the electric current density. The strain rate hardening for high speed experiment was neglected. The strength hardening coefficient K and strain-hardening exponent n are determined from the true stress–strain data without electric current (A = 0) as shown in Figure 9. The electro-plastic effect constant B and electric current sensitivity index c are determined by interpolating experimental results (dotted line) continuously applied to the current of 100 A to 500 A during the tensile test as a curve fitting function in Equation (4). Using the parameters obtained through this process, the expected flow stress for each current is indicated by the solid line as shown in Figure 10. Table 3 lists values of K, n, B, c of Al5052 for electro-plastic effect.

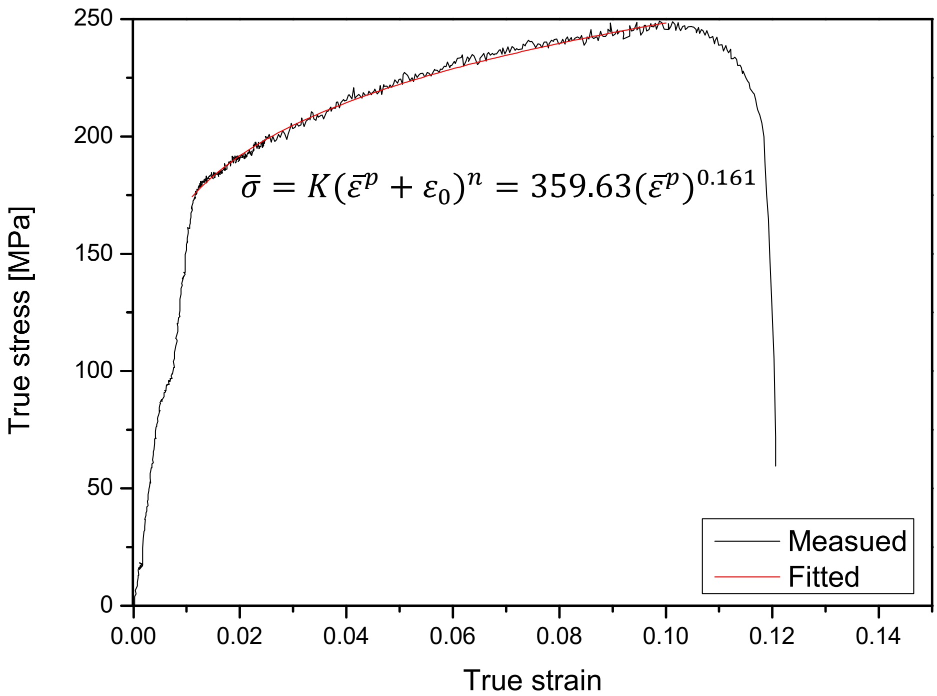


Figure 9. True stress strain data of Al5052 from uniaxial tests.

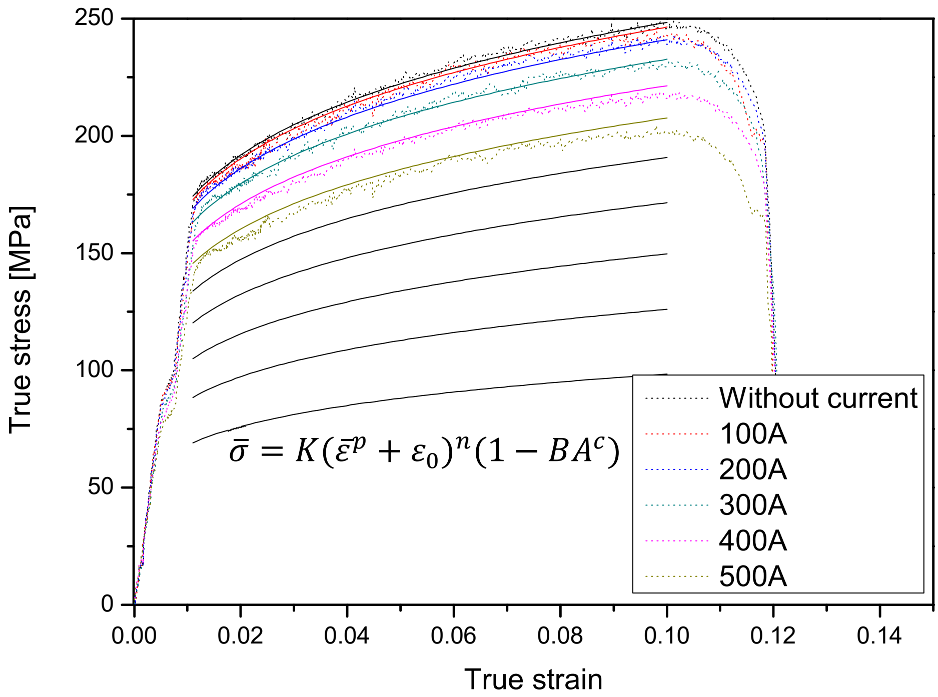


Figure 10. True stress–strain data of Al5052 from uniaxial tests at several electric current pulse.

Table 3. Material properties of Al5052 with electro-plastic effect.

Coefficient	*K* [MPa]	*n*	*B* [1/A]	*c*
Al5052	359.6302	0.16063	8.1425E-7	1.8673

3.2. Verification of the Constitutive Model Using UMAT in LS-DYNA

Finite element analysis of the uniaxial tensile test experiments was performed with the electrical structural finite element model described previously using the electric current dependent UMAT subroutine. The purposes of the numerical analysis were first to check the validity of the assumption that thermal strains are negligible in the electro-plastic effect forming process, and then to verify the accuracy of both the constitutive model as Equation (4) and the developed UMAT to predict forming in the aluminum sheet with electric current pulse. This was done to insure accurate analysis corresponding to the experimental tests. A finite element model of the uniaxial tensile test was developed, as shown in Figure 11. It is meshed using 8-node continuum elements for the specimen geometry. Figure 12 shows the experimental and the electro-mechanical simulation results of uniaxial tensile test of Al5052 without electric current pulse. Figure 13 shows the experimental and electro-mechanical simulation results of uniaxial tensile test of Al5052 with an electric current pulse of 1000 A (222 A/mm^2). The experimental results accurately agree with the numerical prediction of stress–strain curve at this electric current pulse. As could be seen from this plot, the constitutive model taking into account the electro-plastic effect was capable of accurately predicting the material deformation behavior under electric current.

Figure 11. Numerical simulation model for uniaxial tensile test.

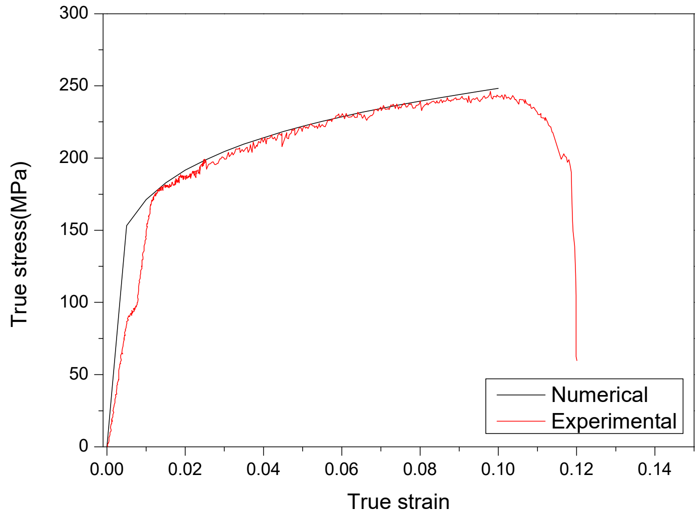


Figure 12. Experimental and the electro-mechanical simulation results of uniaxial tensile test of Al5052 without electric current pulse.

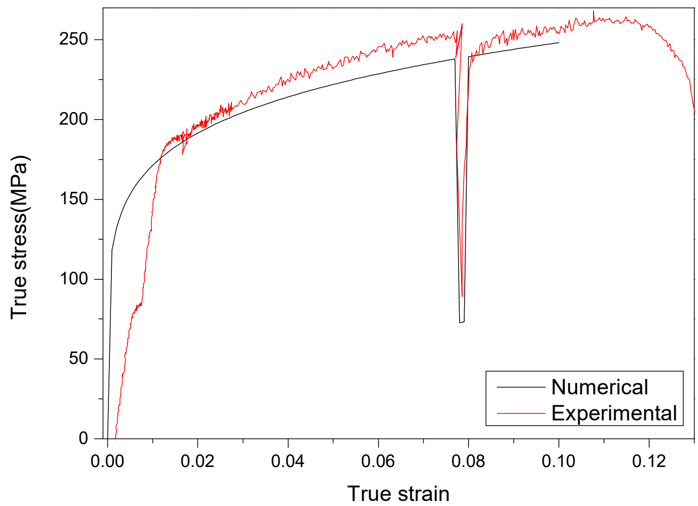
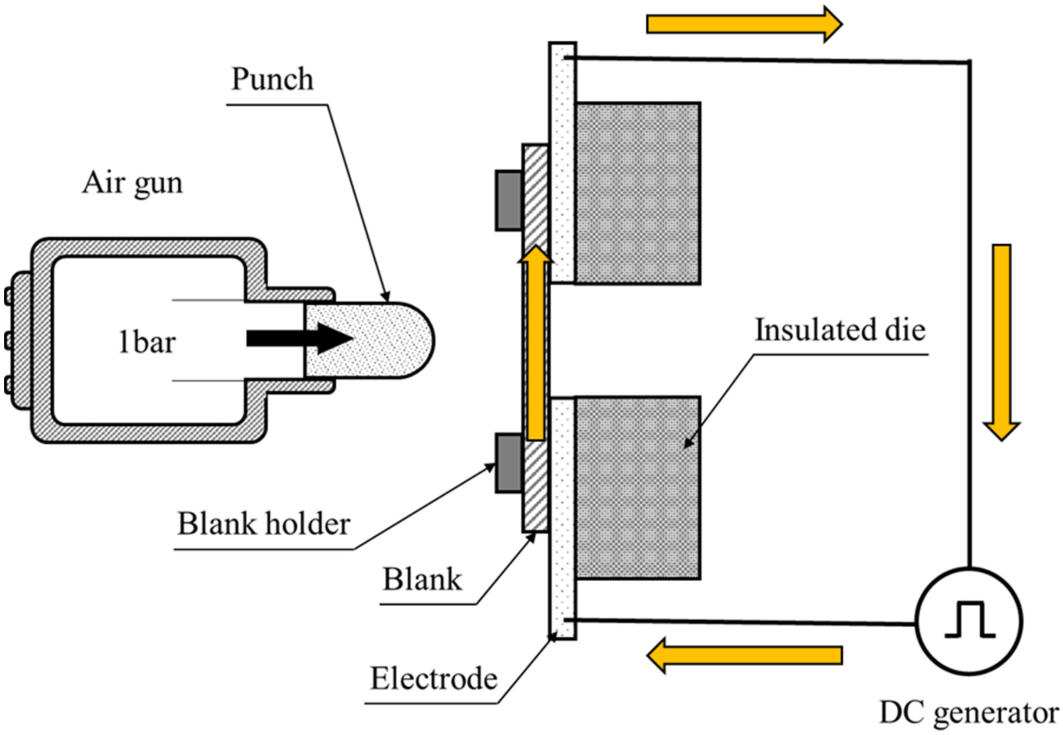


Figure 13. Experimental and electro-mechanical simulation results of uniaxial tensile test of Al5052 with an electric current pulse of 1000 A (222 A/mm^2).

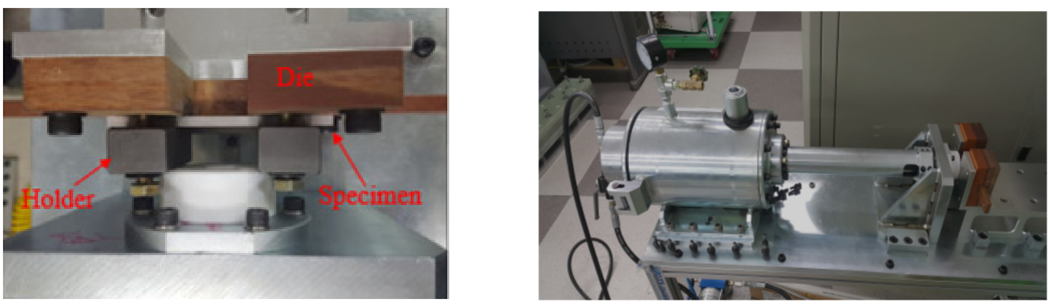
4. High-Speed Forming with Single Current Pulse

In order to demonstrate the advantages of passing electric current pulses during the forming process, the high-speed forming test was devised to complete the forming process during electric current flow. Because of the stress drop to take place during a very short period of time, it is also required a special forming process to deform the material within that time. High-speed forming process as one of the special forming method was employed. It might be shown that the high speed forming process with current pulse proposed in this study (PCT/KR2015/013027) [17] can be applied to cold forming process of high strength steel which cannot be generally formed at room temperature due to high strength. The equipment for high-speed forming test with an electric current pulse includes an air-gun, punch, blank, blank holder, insulated die, electrode, and electric current generator as illustrated in Figure 14. The blank, which has a shape similar to that of the tensile test specimen, was fixed on the insulated die with blank holder. The copper electrodes, which were mounted on the insulated die, were kept in contact with the blank and electric current generator to apply the electric current pulse. The air gun is an apparatus for a highly specialized launcher designed to generate high velocities. It is used for the punch launched with high speed to collide to the blank, leading to high-speed forming process. The air-gun launched the 6 g punch at 10 m/s employing pressure of

1 bar. The launch of the punch and the electric current application of the specimen were performed simultaneously. Forming time is less than 10 ms, so whole forming process can be done for duration time less than 100 ms. The punch deforms the blank and comparison of forming depths with an electric current pulse and without an electric current pulse is carried out. The tests had similar parameters; each test was repeated three times. A 3D scanning measurement instrument was employed to gauge the Z-displacement along the line A-A′ illustrated in Figure 15. The results (H_u and H_l) were measured as illustrated in Figure 15c. As can be observed in Table 4, during the forming process, an electric current pulse affects Al5052 by increasing the forming height. The displacement along the center line of Al5052 specimen is also illustrated in Figure 15. As revealed by experimental results obtained during the high-speed forming with 222 A/mm^2 electric current density, the forming height under the electric current pulse is 182~201% of that without the electric current pulse. Thus, we conclude that forming with electro-plastic effect is more effective than conventional cold forming.

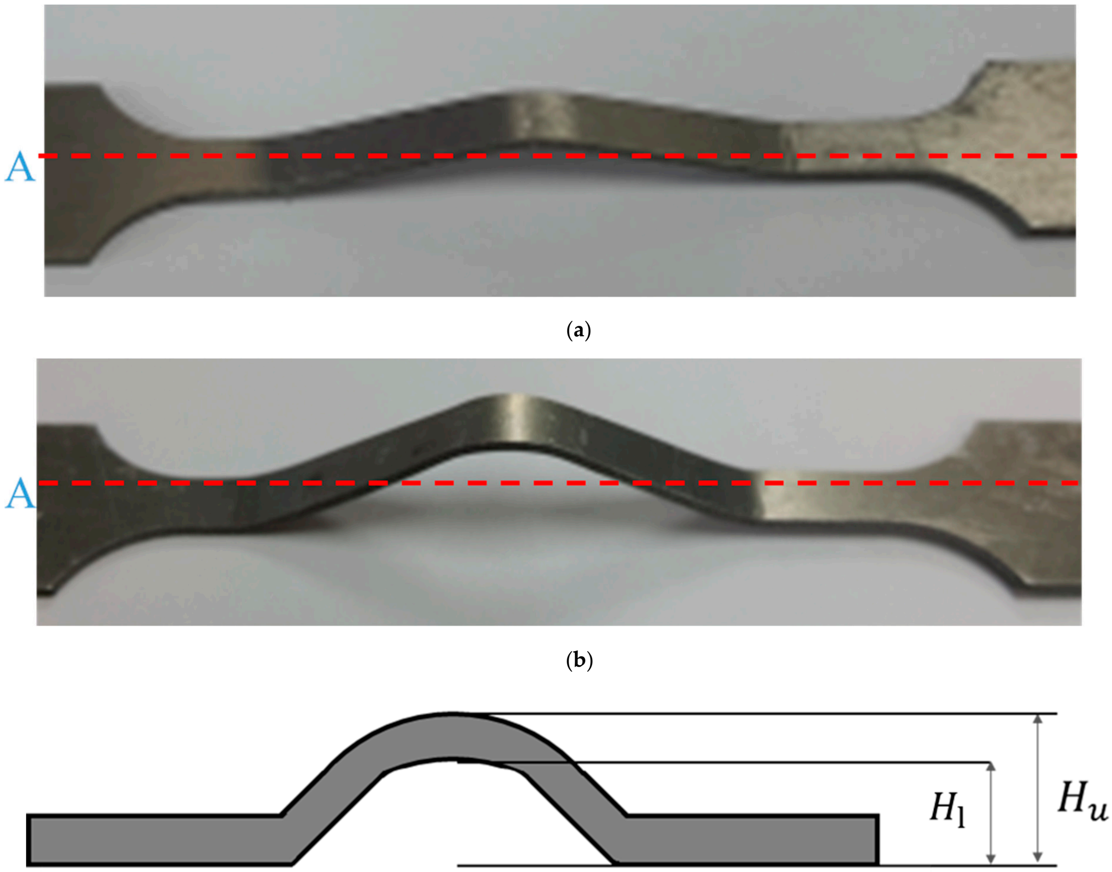


(**a**)



(**b**)

Figure 14. The high-speed forming test with electric current pulse. (**a**) Schematic of high speed forming test. (**b**) Set up for high speed forming test.



(**a**) (**b**) (**c**)

Figure 15. High-speed forming test (**a**) without electric current flow (**b**) with electric current flow in Al5052 and (**c**) high speed forming sample.

Table 4. Forming height of high speed forming.

Case No.	**Al5052**		**Improvement Rate**
	With Current	**Without Current**	
#1	H_u: 9.61 H_l: 8.62	H_u: 5.31 H_l: 4.31	181% 200%
#2	H_u: 9.57 H_l: 8.57	H_u: 5.25 H_l: 4.26	182% 201%
#3	H_u: 9.56 H_l: 8.56	H_u: 5.25 H_l: 4.25	182% 201%
Avg.	H_u: 9.58 H_l: 8.58	H_u: 5.27 H_l: 4.26	182% 201%

The electric current-dependent material model is implemented to simulate the high-speed forming process with electro-plastic effect. A finite element model of the high-speed forming process was developed, as shown in Figure 16. The purposes of the numerical analysis were first to check the validity of the assumption that forming process is performed for the duration time in the high-speed forming process, and then to verify the accuracy of the developed UMAT subroutine to predict forming height in the aluminum sheet under electric current. The Variation of maximum strain rate with time is shown in Figure 17. The overall process has a strain rate of up to 300/s^{-1}. The maximum strain rate less than about 1000/s^{-1} have little effect on strain rate, it is reasonable to neglect strain hardening at the model construction phase [18]. Figure 18 illustrates numerical simulation result of high-speed forming process with and without an electric current pulse, respectively. In order to verify the simulation result, the numerical displacement data was compared with the experimental displacement data in the A-A′ cross-sectional view as illustrated in Figure 18. Figure 19 presents a comparison of the A-A′ section profiles between experimental results and simulation results. As can be observed, the measured experimental profiles and numerical final shape were in good agreement, although the height of the simulated portion at certain locations was marginally larger than that of the experimental data. The minor discrepancies are supposed to have occurred in the numeral simulation because the current is applied uniformly throughout the specimen, but not ideally uniformly and uniformly in the experiment. In case of a high-speed forming process without an electric current pulse, the numerical displacement data is similar to the experimental displacement data as in the previous case. In the case of the high-speed forming process with electric current pulse, an error of ~1 mm is observed at the central portion and overall deformed portion.

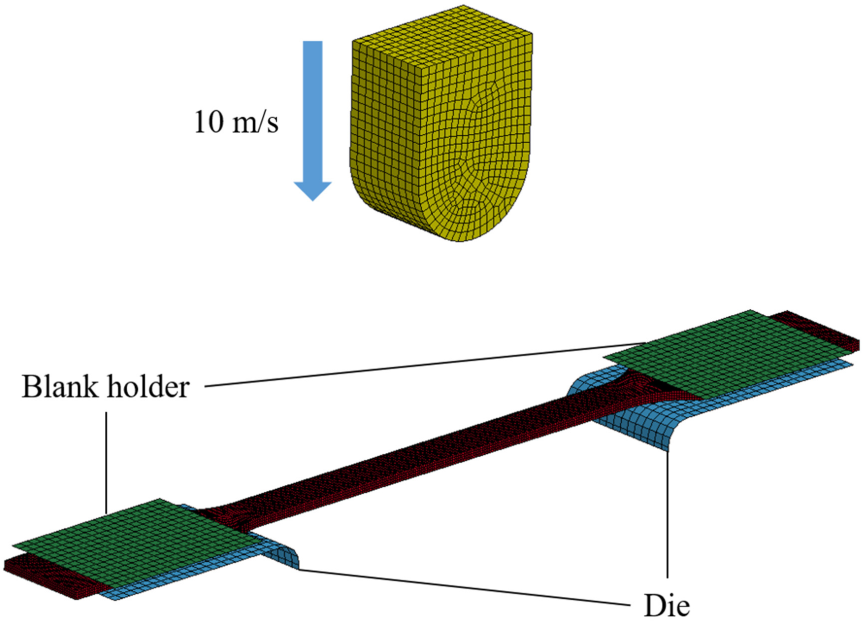


Figure 16. Numerical simulation model shape for high-speed forming process.

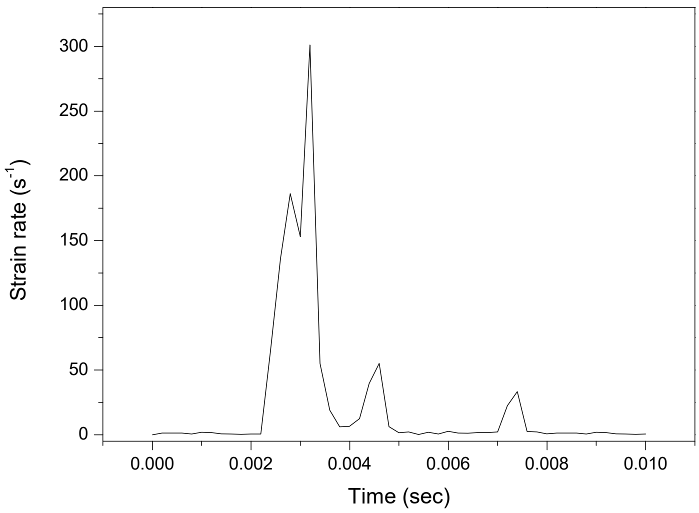


Figure 17. Variation of maximum strain rate with time.

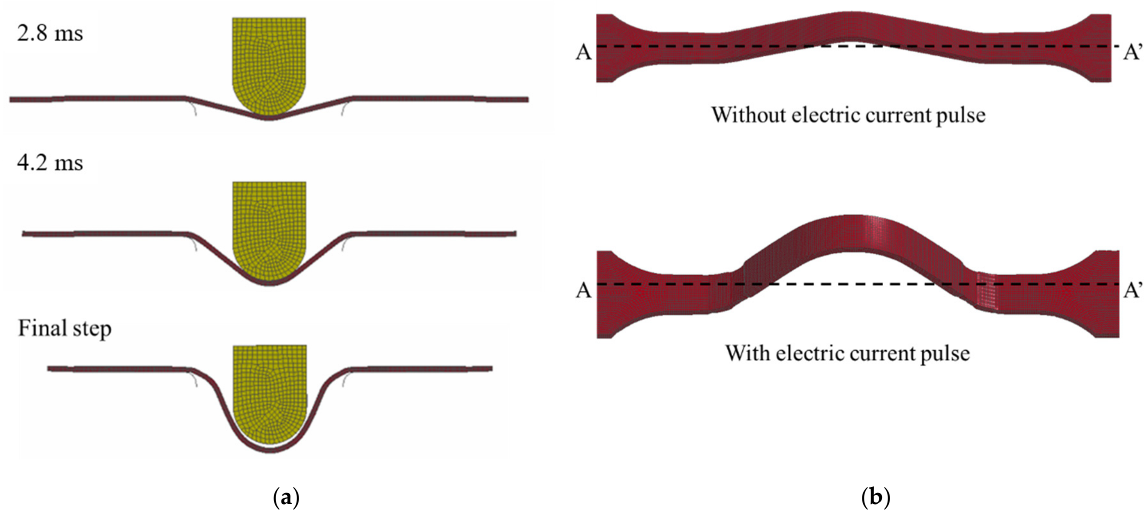


Figure 18. (**a**) 2-D schematic view of deformation behavior with time step and (**b**) simulation result of high-speed forming with and without electric current pulse.

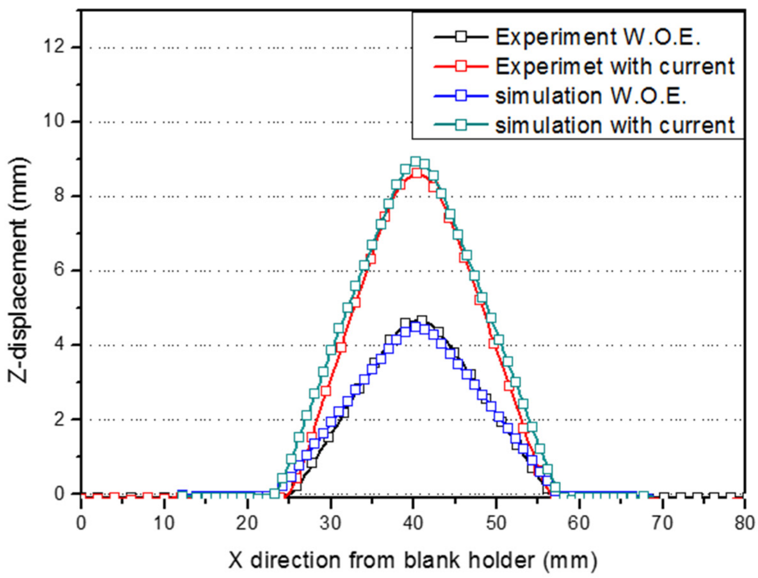


Figure 19. Comparison of simulation and experiment result in Z-displacement in Al5052.

5. Conclusions

In this study, the change of flow stress of Al5052 alloy sheet subjected to single current pulse in uniaxial tensile state was analyzed through experiments and numerical simulations. Through results of this studies, the following conclusions were obtained.

In a tensile test with electric current, the flow stress decreases according to the current intensity and the current application time. The amount of decrease in the flow stress is proportional to the square of the current intensity and the current duration time. In order to establish reliable numerical model taking into account the electro-plastic effect, the electric current-dependent constitutive mode was proposed, which neglects the temperature change due to the application of current and configures the flow stress drop only depending on the current pulse. The developed electric current-dependent material model was then successfully implemented as a UMAT subroutine in the finite element code LS-DYNA to be used in an electro-mechanical finite element analysis of the electro plastic effect of aluminum products. Finite element analysis with the developed electro-mechanical constitutive model accurately indicated the deformation behavior in high-speed forming under electric current as compared with experimental results.

Consequently, it is concluded that the application of a high-speed forming process synchronizing with the stress variation that occurs for a very short period of time due to electric current pulse may be utilized in a cold forming process with lower forming force than required.

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Conflicts of Interest: The authors declare no conflict of interest.

References

1. Tang, G.; Zheng, M.; Zhu, Y.; Zhang, J.; Fang, W.; Li, Q. The application of the electro-plastic technique in the cold-drawing of steel wires. *J. Mater. Process. Technol.* **1998**, *84*, 268–270. [CrossRef]
2. Zimniak, Z.; Radkiewicz, G. The electroplastic effect in the cold-drawing of copper wires for the automotive industry. *Arch. Civ. Mech. Eng.* **2008**, *8*, 173–179. [CrossRef]
3. Egea, A.S.; Peiró, J.J.; Signorelli, J.W.; Rojas, H.G.; Celentano, D.J. On the microstructure effects when using electropulsing versus furnace treatments while drawing inox 308L. *J. Mater. Res. Technol.* **2019**, *8*, 2269–2279. [CrossRef]
4. Ross, C.D.; Irvin, D.B.; Roth, J.T. Manufacturing aspects relating to the effects of direct current on the tensile properties of metals. *J. Eng. Mater. Technol.* **2007**, *129*, 342–347. [CrossRef]
5. Potapova, A.A.; Stolyarov, V.V. Relaxation effect of pulse current on Ti50.0Ni50.0 structure during rolling. *Mater. Sci. Technol.* **2015**, *31*, 1541–1544. [CrossRef]
6. Wang, X.; Sánchez Egea, A.; Xu, J.; Meng, X.; Wang, Z.; Shan, D.; Guo, B.; Cao, J. Current-induced ductility enhancement of a magnesium alloy AZ31 in uniaxial micro-tension below 373 K. *Materials* **2019**, *12*, 111. [CrossRef] [PubMed]
7. Egea, A.J.S.; Rojas, H.A.G.; Celentano, D.J.; Travieso-Rodríguez, J.A.; i Fuentes, J.L. Electroplasticity-assisted bottom bending process. *J. Mater. Process. Technol.* **2014**, *214*, 2261–2267. [CrossRef]
8. Green, C.R.; McNeal, T.A.; Roth, J.T. Springback elimination for Al-6111 alloys using electrically-assisted manufacturing (EAM). *Trans. N. Am. Manuf. Res. Inst.* **2009**, *37*, 403–410.
9. Kim, W.; Yeom, K.H.; Thien, N.T.; Hong, S.T.; Min, B.K.; Oh, S.I.; Kim, M.J.; Han, H.N.; Lee, H.W. Electrically assisted blanking using the electroplasticity of ultra-high strength metal alloys. *CIRP Ann. Manuf. Technol.* **2014**, *63*, 273–276. [CrossRef]
10. Andrawes, J.S.; Kronenberger, T.J.; Perkins, T.A.; Roth, J.T.; Warley, R.L. Effects of DC current on the mechanical behavior of AlMg1SiCu. *Mater. Manuf. Process.* **2007**, *22*, 91–101. [CrossRef]
11. Fan, R.; Magargee, J.; Hu, P.; Cao, J. Influence of grain size and grain boundaries on the thermal and mechanical behavior of 70/30 brass under electrically-assisted deformation. *Mater. Sci. Eng.* **2013**, *574*, 218–225. [CrossRef]
12. Breda, M.; Calliari, I.; Bruschi, S.; Forzan, M.; Ghiotti, A.; Michieletto, F.; Spezzapria, M.; Gennari, C. Influence of stacking fault energy in electrically assisted uniaxial tension of FCC metals. *Mater. Sci. Technol.* **2017**, *33*, 317–325. [CrossRef]
13. Ruszkiewicz, B.J.; Grimm, T.; Ragai, I.; Mears, L.; Roth, J.T. A review of electrically-assisted manufacturing with emphasis on modeling and understanding of the electroplastic effect. *J. Manuf. Sci. Eng.* **2017**, *139*, 110801. [CrossRef]
14. Conrad, H. Electroplasticity in metals and ceramics. *Mater. Sci. Eng.* **2000**, *287*, 276–287. [CrossRef]
15. ASTM International. *ASTM E8/E8M-09. Standard Test Methods for Tension Testing of Metallic Materials*; ASTM International: West Conshohocken, PA, USA, 2011.
16. Gronostajski, Z. The constitutive equations for FEM analysis. *J. Mater. Process. Technol.* **2000**, *106*, 40–44. [CrossRef]

17. Kim, J.; Kang, B.S.; Noh, H.G. Ultra-High-Speed Forming Method Using Electroplasticity Effect. U.S. Patent Application No. 15/533,149, 16 November 2017.
18. Yi, F.; Zhu, Z.; Zu, F.; Hu, S.; Yi, P. Strain rate effects on the compressive property and the energy-absorbing capacity of aluminum alloy foams. *Mater. Charact.* **2001**, *47*, 417–422. [CrossRef]