DOI: 10.1007/s12541-014-0458-y

Effect of Electric Current Density on the Mechanical Property of Advanced High Strength Steels under Quasi-Static Tensile Loads

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KEYWORDS: Advanced high strength steels, Electric current density, Mechanical property, Springback

The effect of a single pulse of electric current on the mechanical property of advanced high strength steels (AHSS) under quasi-static tensile loads is investigated by experiments. During a typical quasi-static tensile test, electric current is applied to a specimen for a short duration (less than 1 second) while the specimen is in plastic region. The stress-strain curve shows that the flow stress almost instantly decreases significantly (stress-drop) when the electric current is applied, while the tensile strength from the following stress-strain curve after the short pulse of electric current is not changed much. The experimental result suggests that the stress-drop at the moment of a short pulse of electric current can be effectively used to reduce the springback of material, as successfully demonstrated in the present study.

Manuscript received: April 15, 2013 / Revised: January 8, 2014 / Accepted: April 4, 2014

1. Introduction

As an effort to improve the fuel efficiency, automotive industries are rapidly increasing the use of lightweight materials in vehicle structures. Advanced high strength steel (AHSS) is considered a lightweight ferrous alloy and may be able to reduce the weight of structures while at the same time enhancing the crashworthiness. However, the high strength of AHSS may induce a considerable amount of springback after forming and make the design of the forming process very difficult.

Various studies[1-3] have shown that the material property of a metal can be altered by simply applying electric current to the metal during deformation (electroplasticity) without a significant increase in temperature. In addition to the classical work by Troitskii,[1] the studies of Conrad[2,3] show that plasticity and the phase transformation of various metals and ceramics are affected by pulsed or continuous electric current.

Even though a completely satisfactory explanation of the mechanism of electroplasticity of metals has not yet been given, the phenomenon of electroplasticity is very interesting to researchers and industries in the field of metal forming. In recent efforts to implement electroplasticity in metal forming processes, Ross et al.[4] and Perkins et al.[5] showed that the presence of continuous electric current during plastic deformation could significantly reduce the flow stress of metals. However, continuously applied electric current reduced the maximum achievable elongation of the metal under tension,[4] while the formability of the metal increased significantly with continuous electric current under compression.[5] The decrease in the maximum elongation of a metal under continuous electric current may be explained by the fact that the cross-sectional area of the specimen continuously decreases under tension, thus causing a continuous increase in the electric energy pre unit area (electric energy density), which causes excessive heating, eventually contributing to premature failure of the specimen.

For the electroplasticity of a metal under tension, attempts to overcome the disadvantages of the reduced maximum elongation under continuous electric current led researchers to pulse the electric current instead of applying it continuously to specimens under tension. For example, Roth et al.[6] achieved elongation close to 400% of the gage length by applying pulsed electric current to 5754 aluminum alloy specimens under tension. One interesting aspect of the stress-strain behavior of metal under pulsed electric current is that the flow stress is significantly reduced (stress-drop) at the moment of electric current, and shows a rapid recovery as soon as the electric current is removed. As a result, a very unique serrated stress-strain curve is obtained under pulsed electric current. Based on the nearly instant stress-drop at the pulse of electric current, Green et al.[7] suggested that the springback in forming of aluminum 6111 alloy sheets can be reduced or even eliminated by applying a single pulse of high current electricity at the final moment of deformation before removal of the forming load. However, the effect of the pulse of high current electricity on the post-process mechanical property of the given alloy needs to be investigated before the electrically assisted springback reduction process suggested by Green et al.[7] can be implemented in commercial manufacturing processes.

In the present study, the effect of a single pulse of electric current on the mechanical property of AHSS is investigated by experiments. First, the effect of the electric pulse parameters on the nearly instant stress-drop during tensile deformation is presented. Next, the hardening behavior and tensile strength of the given AHSS after a pulse of electric current are discussed. The effect of the electric pulse parameters on the microstructure of tensile deformed AHSS is also briefly discussed for the purpose of completeness. Finally, based on the result of tensile tests with a single pulse of electric current, the effectiveness of electroplasticity in springback reduction for AHSS sheet metal forming is demonstrated using a simple experimental set-up.

2. Experimental Set-up

SPFC 980DP steel sheets 1 mm in thickness were used for experiments. The chemical composition of the selected AHSS is listed in Table 1. For normal quasi-static tensile tests (baseline tests) and quasi-static tensile tests with a single pulse of electric current, typical tensile specimens with 10 mm gage width and 50 mm gage length were fabricated by laser cutting along the rolling direction of the sheet.

For the quasi-static tensile tests with a single pulse of electric current, the electric current was created using a Vadal SP-1000U welder (Hyosung, South Korea) with a programmable pulse controller and was applied to the specimen as schematically shown in Fig. 1. Also, a set of insulators made of bakelite was inserted between the specimen and each grip to isolate the electricity from the testing equipment. The magnitude of the current applied to the specimen was monitored and confirmed using a digital clamp-on Ammeter, while the force history was recorded as a function of displacement using a PC-based data acquisition system.

The quasi-static tensile tests were conducted using a universal testing machine with a fixed displacement rate of 2.5 mm/min until fracture. For the quasi-static tensile tests with a single pulse of electric current, the electric current was applied to the specimen over a given duration at a tensile displacement of 1.5 mm (corresponding nominal strain of 0.025) without stopping the tensile displacement, as schematically shown in Fig. 2. In the present study, the current density based on the cross-sectional area of the specimen at the moment of the pulse of electric current (true current density ρ_{i_t}) and the duration of the current (pulse duration t_d) were used as experimental parameters (electric pulse parameters).

Nine different sets of electric pulse parameters (group I) were employed for parametric study by combining three different true current densities and three different pulse durations, as listed in Table 2. To verify the repeatability of the result, at least three specimens were tested for each parameter set. In addition to the nine different sets of electric pulse parameters in group I, three different sets of electric pulse parameters (group II) giving the same electric energy density were employed to investigate the effect of the electric energy on the

Table 1 The chemical composition of SPFC 980DP steel sheets provided by the manufacturer

Ferrous alloy	Chemical compositions*					
	Alloying element (wt %)					
	C	Si	Mn	P	S	Al
SPFC 980DP	0.16	1.28	2.01	0.018	0.003	0.035

*Fe is at balance.

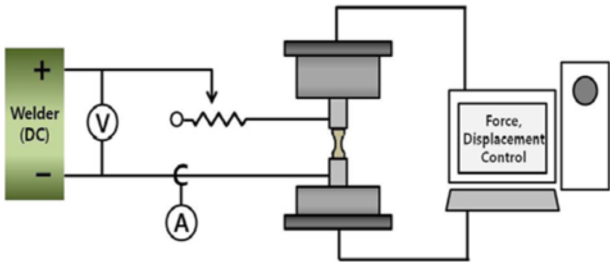

Fig. 1 A schematic of the experimental set-up

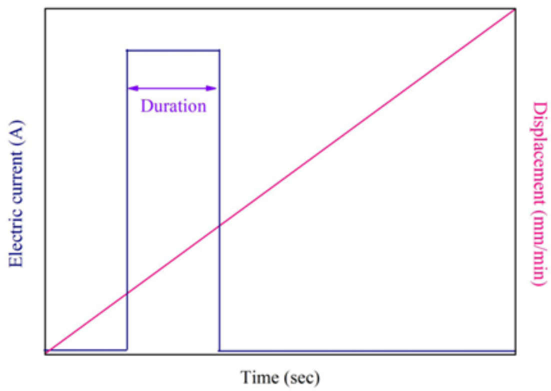

Fig. 2 A schematic of the process of applying a pulse of electric current during tensile displacement

Table 2 Electric pulse parameters

Parameter set	Current density (A/mm^2)	Pulse duration (sec)
Group I*	40, 50, 60	0.4, 0.8, 1.2
Group II**	40	1.00
	50	0.64
	60	0.44

*Total of nine different sets; **Three different sets inducing the same electric energy density of 0.736 J/mm^3

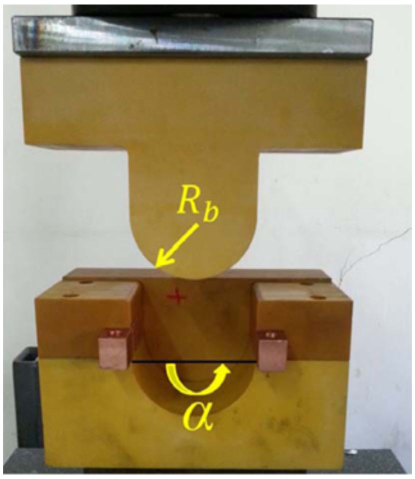

Fig. 3 The U-bending fixture

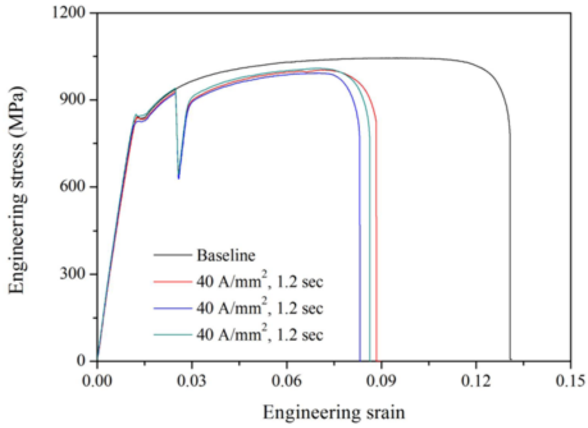

Fig. 4 The repeatability of the experimental results

mechanical property of the selected AHSS.

For microstructural analysis, a normal tensile test (baseline test) and tensile tests with two different sets of electric pulse parameters, giving different electric energy densities were manually stopped at the tensile displacement of 3 mm (corresponding nominal stain of 0.049), and the specimens were removed from the test. The samples for electron back-scatter diffraction (EBSD) analysis were prepared perpendicular to the tensile direction of the specimens removed from the test. The samples were electrolytically polished in a 50 ml pechloric acid + 950 ml methanol solution using a Lectropol-5 electrolytic polisher (Struers, Denmark) after standard metallographic grinding. The crystallographic orientation was analyzed by EBSD system equipped with a HKL Channel 5 and INCA Crystal (Oxford Instruments, United Kingdom). The accelerating voltage, probe current and the working distance were 20 kV, 4 nA, and 15 mm, respectively.

Finally, reduction of springback by a single pulse of electric current was demonstrated using a simple U-bending fixture shown in Fig. 3 (bending angle α of 180° and bend radius R_b of 40 mm). The U-bending specimens with 200 mm length and 50 mm width were prepared along the rolling direction. The U-bending tests were conducted with a cross-head speed of 20 mm/min and a load limit of 1668 N. Once the load reached the limit, the cross-head was stopped and different magnitudes of electric current were applied to the specimen with a constant duration of 0.5 sec before the specimen was unloaded. The resultant springback of the specimen was then measured after removal from the U-bending fixture.

3. Results and Discussion

For all the electric pulse parameter sets used in the present study, the repeatability of the experimental result is quite good, as shown in Fig. 4. Under quasi-static tensile loads, the flow stress of the selected AHSS significantly decreased nearly instantly (defined as a stress-drop) when the electric current was applied to the specimen, as shown in Fig. 4. Once the electric current was removed from the specimen, the flow stress of the material rapidly increased, and then showed typical strain-hardening behavior. This unique mechanical behavior under a pulse of electric current agrees well with the previously reported results for aluminum or magnesium alloys.[6-9]

The temperature measurement (not shown here) using an infra-red thermal imaging camera showed that the average temperature over the specimen gage section over the duration of electric current was only approximately 100°C. Therefore, as already reported in the literature,[4-9] the mechanical behavior under the pulse of electric current for the selected AHSS may not be simply understood as a consequence of the thermal effect of applied electric current.

It is obvious that the stress-drop and the subsequent hardening behaviors of the given AHSS are significantly affected by the both of applied electric current density and pulse duration, as shown in the representative experimental results in Figs. 5(a) and (b). However as shown by Roh et al.[10] the tensile electroplasticity of metals with pulsed electric current needs to be investigated based on the applied electric energy per unit area (electric energy density), which is a function of the electric current density and pulse duration. This was confirmed by the experimental results obtained using three different sets of electric pulse parameters (group II in Table 2) giving the same true electric energy density, which is based on the cross-sectional area of the specimen at the moment of the pulse of electric current as shown in Fig. 6.

The three different sets of electric pulse parameters resulted in nearly identical stress-strain curves, as shown in Fig. 6, by inducing the same true electric energy density in the specimen at the same engineering strain. The true electric energy density at a pulse of electric current, j, based on the volume of gage section of the specimen at that moment can be simply calculated as[10]

$$j = \frac{J}{V} = \frac{I^2 R t_d}{V} \qquad (1)$$

where J, I, R, t_d, and V represent the electric energy (in J), the electric current (in A), the electric resistance of the specimen (in Ω), the pulse duration (in sec), and the volume of the gage section of the specimen (in mm^3) at the moment of the pulse of electric current, respectively. Note that for the calculation of the electric energy from the three different sets of electric pulse parameters, the electric resistance R of the selected AHSS was assumed to be same for all the three cases. Now, as confirmed by the result in Fig. 6, the tensile electroplastic behavior of the selected AHSS under pulsed electric current may be

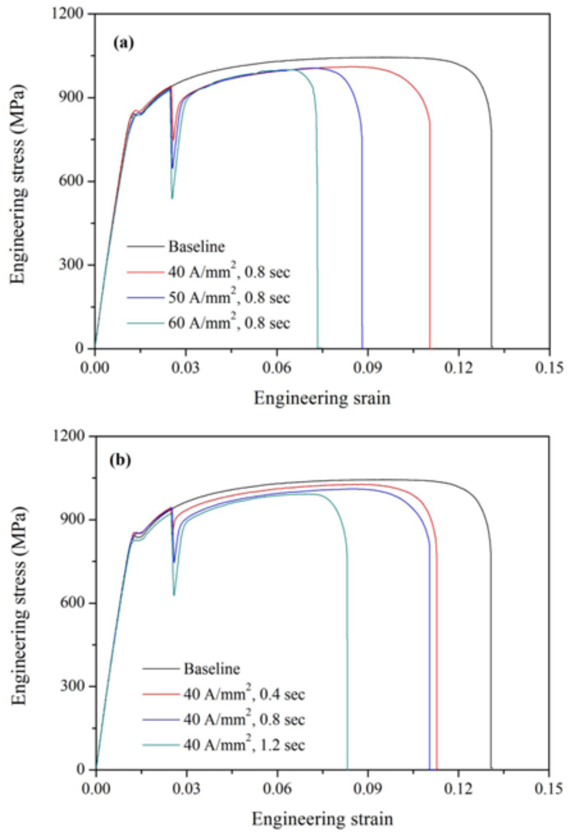

Fig. 5 Representative results showing the effects of (a) the electric current density and (b) the pulse duration on the tensile behavior of the AHSS

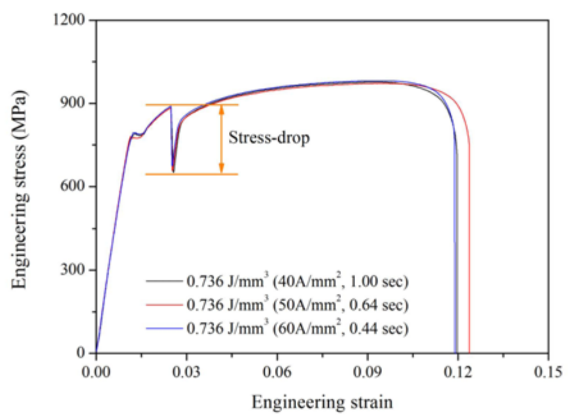

Fig. 6 Experimental results using an identical electric energy density

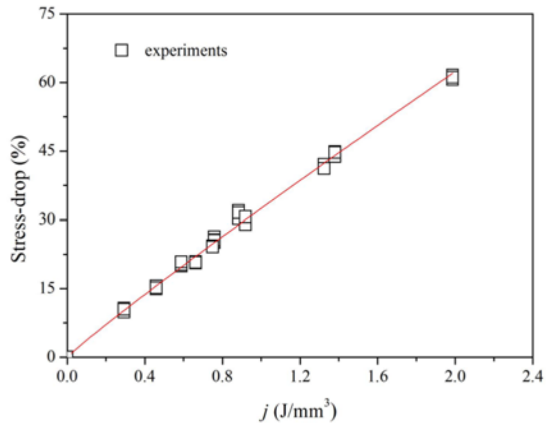

Fig. 7 The stress-drop as a function of the electric energy density

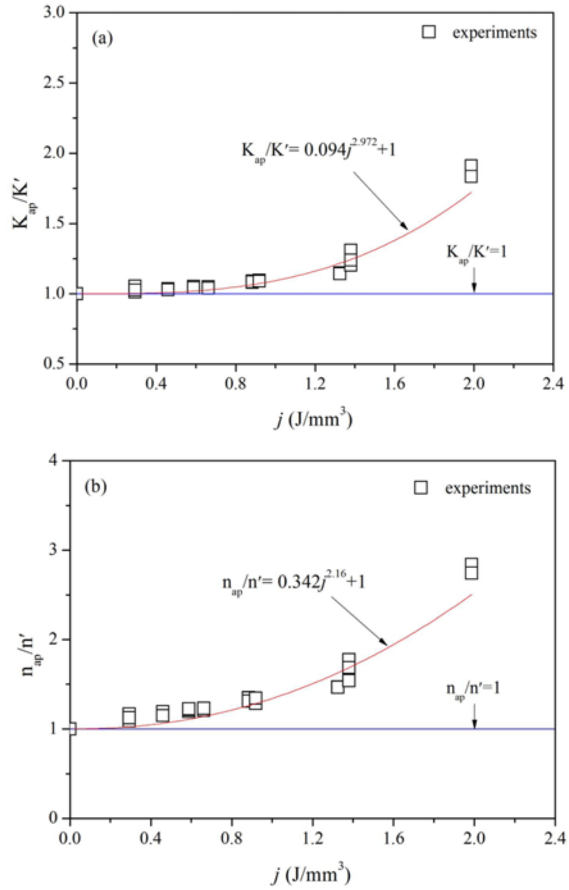

Fig. 8 The effects of the electric energy density on the hardening behavior of the AHSS: (a) K_{ap} (strength coefficient) and (b) n_{ap} (hardening exponent)

discussed using the electric energy density for the given displacement rate (or the strain rate).

The stress-drop, which is probably the most unique characteristic of the stress-strain behavior of the given AHSS under the single pulse of electric current, linearly increased as the electric energy density increased over the given range of electric energy density, as shown in Fig. 7. Also, the electric energy applied to the specimen by the single short pulse of electric current during plastic deformation altered the hardening behavior of the AHSS after the electric current was removed. The strength coefficient K_{ap} and strain hardening exponent n_{ap} after the pulse of electric current, where the subscript *ap* stands for "after-pulse", increased as the electric energy density increased as shown in Figs. 8(a) and (b), respectively. Note that K_{ap} and n_{ap} are normalized by K' and n', respectively, which are calculated from the part of the baseline curve after the nominal strain of 0.025. Therefore, K' and n' correspond to K_{ap} and n_{ap} at j=0, respectively. The increase in the strain hardening coefficients K_{ap} and n_{ap} suggests that the applied electric current induced an annealing effect in the specimen as argued by Kim et al.[11]

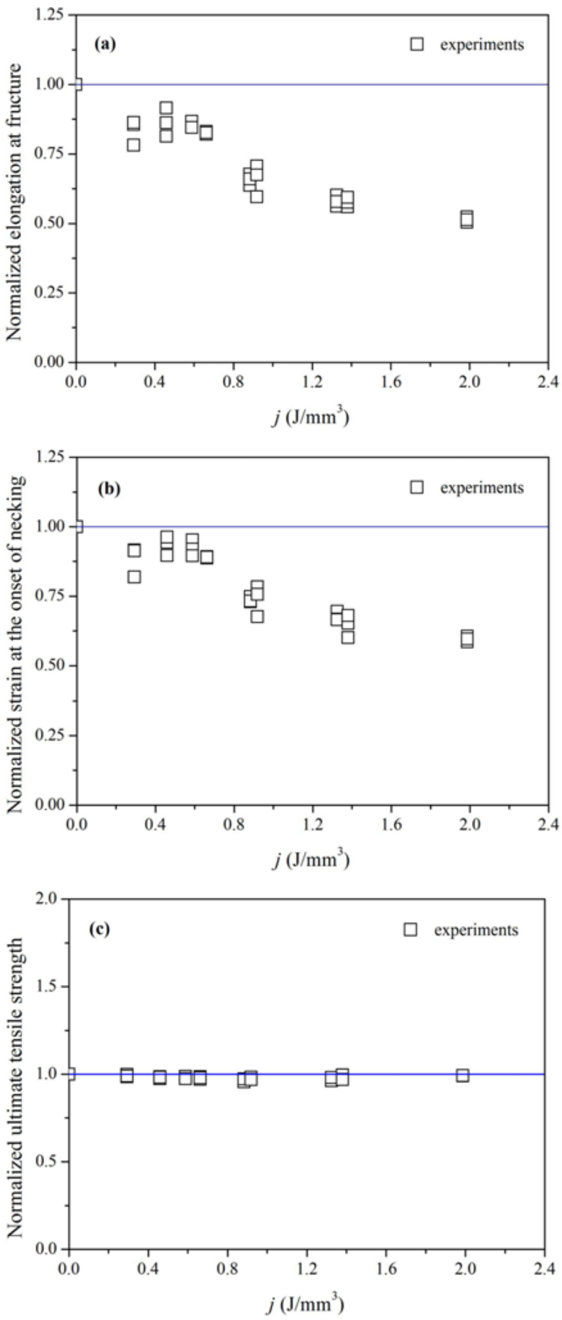

Fig. 9 The effects of the electric energy density on: (a) the elongation at fracture, (b) the strain at the onset of necking, and (c) the UTS of the AHSS; The experimental results were normalized with the corresponding baseline values

As shown in Figs. 8(a) and (b), the dependency of the normalized strength coefficient K_{ap}/K' and the normalized strain hardening exponent n_{ap}/n' on the electric energy density j can be nicely fitted as

$$K_{ap}/K = 0.094j^{2.972} + 1 \tag{2}$$

$$n_{ap}/n = 0.342j^{2.16} + 1 \tag{3}$$

Through the experiments in the present study, both the elongation at fracture and the strain at the onset of necking, which correspond to the

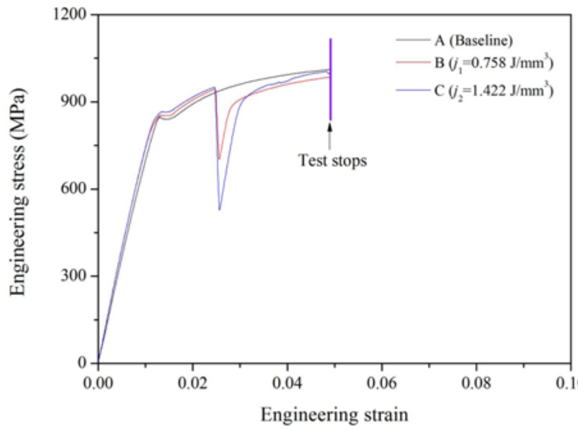

Fig. 10 Experiment for microstructural analysis

strain at the maximum nominal stress, decreased as the electric energy density increased, as shown in Figs. 9(a) and (b), respectively.

The adverse effect of the single pulse of electric current on the ductility of the given AHSS is somewhat surprising, since it has been shown that the ductility of metals is generally increased by applying pulses of electric current during tensile deformation.[6,8,9] A clear explanation for this phenomenon has not yet been provided. We suspect that this adverse effect of the single pulse of electric current on the ductility is related to the dual phases of the given AHSS since a similar adverse effect was observed for precipitation hardened 6XXX aluminum alloys (not shown here).

It is interesting to note that the effect of the single pulse of electric current on the ultimate tensile strength (UTS) of the given AHSS was not significant as shown in Fig. 9(c). The insignificant change in UTS at the increased electric energy density is due to the combined effect of the increased strain hardening parameters and the decreased strain at the UTS. This suggests a quite promising aspect, in that the effect of a single pulse of electric current on the mechanical behavior of the AHSS could be utilized in various practical manufacturing processes without sacrificing the strength of manufactured parts.

The microstructures of the specimens, which were pulsed with j = 0.758 or 1.422 J/mm^3 and then removed from the test at the nominal strain of 0.049 as shown in Fig. 10, were compared with the microstructure of the baseline test specimen removed from the test at the same nominal strain.

Figs. 11(a)~(d) show the EBSD band contrast (BC) image maps, which were scaled to the byte range 0-255 for the AHSS. For grain identification, misorientation angle in the grain boundary definition was set to 10^o. The specimens were expected to have dual phase microstructure consisting of ferrite and martensite as marked in the BC image maps. In crystallographic orientation (loading direction, LD) map (Fig. 12), the red, green and blue colors represent the <001>, <101>, and <111> crystallographic directions parallel to LD of the specimen, respectively. Since the value of nominal strain of 0.049 is not enough to change crystallographic orientation of specimen, similar trend in crystallographic orientation which is strong <101> texture parallel to LD of specimen was observed in both as-received specimen (Fig. 12(a)) and the specimens removed from the test as shown in Fig. 10 (Figs. 12(b)~(d)). If thermal effect from resistive heating is

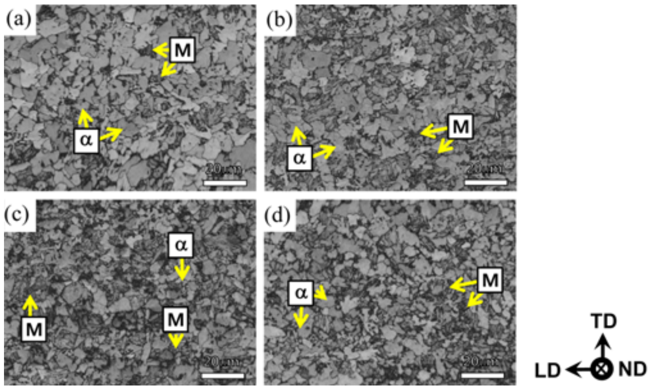

Fig. 11 Band contrast images for specimen (a) of as-received, (b) of uniaxial tensile until nominal strain = 0.049 (Baseline, A in Fig. 10), (c) with j = 0.758 J/mm^3 (single pulse of electric current) and then removed at nominal strain = 0.049 (B in Fig. 10), (d) with j = 1.422 J/mm^3 (single pulse of electric current) and then removed at nominal strain = 0.049 (C in Fig. 10). The symbols α and M marked in images represent ferrite and martensite, respectively

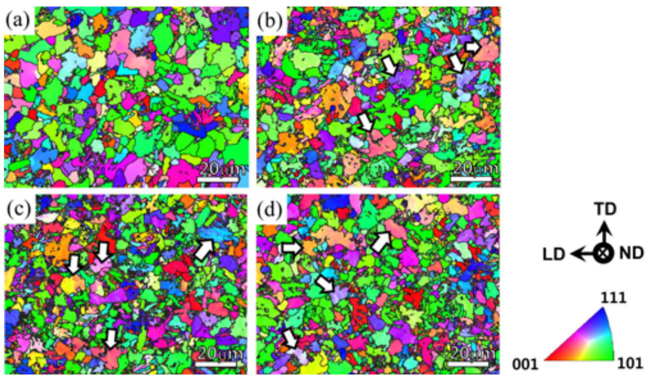

Fig. 12 EBSD orientation (LD) maps for specimen (a) of as-received, (b) of uniaxial tensile until nominal strain = 0.049 (Baseline, A in Fig. 10), (c) with j = 0.758 J/mm^3 (single pulse of electric current) and then removed at nominal strain = 0.049 (B in Fig. 10), (d) with j = 1.422 J/mm^3 (single pulse of electric current) and then removed at nominal strain = 0.049 (C in Fig. 10). The white arrows indicate orientation gradient in deformed ferrite grain

significant, recrystallization and grain growth would be observed in specimens which have undergone the single pulse of electric current even though plastic deformation is not so severe.[10,11]

Therefore, it is confirmed again that the electric energy densities applied to specimen (j = 0.758 and 1.422 J/mm^3) were not high enough to induce a significant thermal effect. In Figs. 12(b)~(d), orientation gradients (white arrows) in deformed ferrite grains were observed. It is known that a stable orientation of BCC ferrite under uniaxial tensile deformation is <101>//LD.[12,13] It can be expected that the orientation gradients are the state to move into <101>//LD.

As demonstrated by Green et al.[7] using aluminum alloy sheets, the stress-drop at the pulse of electric current also can be effectively applied to reduce or even eliminate the springback in bending of the AHSS as shown in Figs. 13(a) and (b). The reduction in springback may be understood as a consequence of the reduction in the amount of elastic recovery due to the stress-drop at the pulse of electric current.[7]

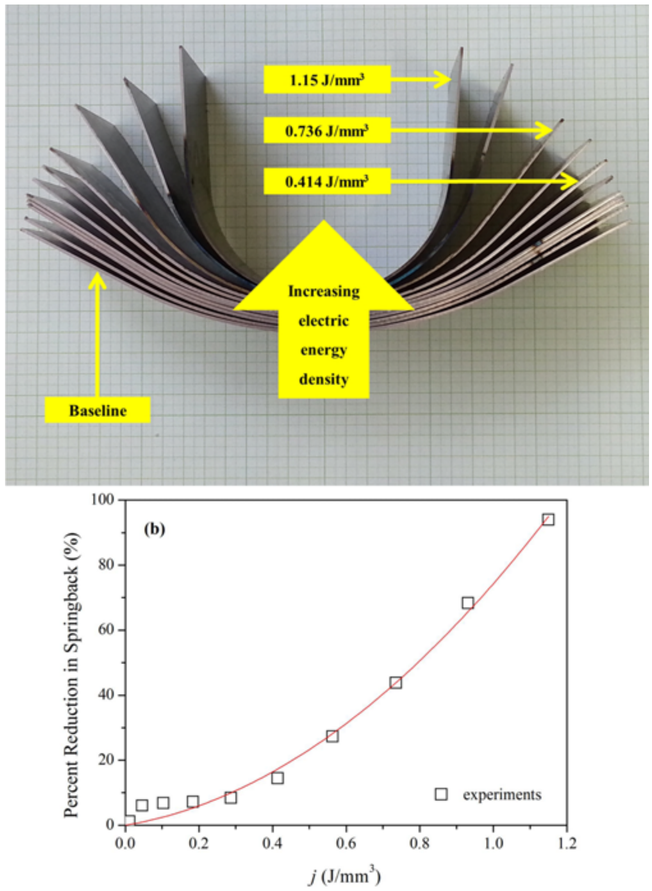

Fig. 13 Springback reduction by a single pulse of electric current: (a) experimental results using the fixture in Fig. 3 and (b) the springback reduction as a function of the electric energy density

As final remarks, note that Eqs. (2) and (3) do not accommodate the effect of the different magnitudes of the strain prior to the pulse of electric current (pre-strain), as the electric current was applied to the specimen at the same tensile strain in all tests in the present study. Therefore, as a future work, the empirical relationship in Eqs. (2) and (3) needs to be expanded to include the effect of pre-strain by conducting additional experiments with different tensile displacements (or strains) at the instant of the pulse of electric current.

4. Conclusions

The effect of a single pulse of electric current on the mechanical property of AHSS under quasi-static tensile loads was investigated by experiments. Under quasi-static tensile loads, the flow stress of the selected AHSS showed a nearly instant stress-drop at a pulse of electric current. The experimental result shows that the magnitude of the stress-drop and the following hardening behaviors of the AHSS strongly depend on the electric energy density, which is a function of the electric current density and the pulse duration. The hardening behavior after the pulse of electric current was well described as a function of the applied electric energy density. Even though the ductility of the AHSS was adversely affected by the single pulse of electric current, the UTS of the

AHSS was not significantly changed due to the increased strain hardening parameters after the pulse of electric current. As demonstrated in the present study, the unique mechanical behavior of the AHSS under a single pulse of electric current can be effectively utilized in various metal forming processes.

ACKNOWLEDGEMENT

This work (Grants No. C0020849) was supported by Business for Academic-industrial Cooperative establishments funded by Korea Small and Medium Business Administration in 2013. Moon-Jo Kim and Heung Nam Han were sponsored by POSCO (2013Z029).

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