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EFFECT OF ELECTRICAL PULSING ON VARIOUS HEAT TREATMENTS OF 5XXX SERIES ALUMINUM ALLOYS

Wesley A. Salandro, Joshua J. Jones, Timothy A. McNeal, and John T. Roth[1]
Penn State Erie, The Behrend College
Department of Mechanical Engineering
Erie, PA, USA
[1]Contact Author

Sung–Tae Hong[2] and Mark T. Smith
Pacific Northwest National Laboratory
Energy Materials and Manufacturing Group
Richland, WA, USA
[2]Currently at University of Ulsan, School of Mechanical and Automotive Engineering, South Korea

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ABSTRACT
Previous studies have shown that the presence of a pulsed electrical current, applied during the deformation process of an aluminum specimen, can significantly improve the formability of the aluminum without heating the metal above its maximum operating temperature range. The research herein extends these findings by examining the effect of electrical pulsing on 5052 and 5083 Aluminum Alloys. Two different parameter sets were used while pulsing three different heat treatments (As Is, 398°C, and 510°C) for each of the two aluminum alloys. For this research, the electrical pulsing is applied to the aluminum while the specimens are deformed, without halting the deformation process. The analysis focuses on establishing the effect the electrical pulsing has on the aluminum alloy's various heat treatments by examining the displacement of the material throughout the testing region of dogbone shaped specimens. The results from this research show that pulsing significantly increases the maximum achievable elongation of the aluminum (when compared to baseline tests conducted without electrical pulsing). Significantly reducing the engineering flow stress within the material is another beneficial effect produced by electric pulsing. The electrical pulses also cause the aluminum to deform non-uniformly, such that the material exhibits a diffuse neck where the minimum deformation occurs near the ends of the specimen (near the clamps) and the maximum deformation occurs near the center of the specimen (where fracture ultimately occurs). This diffuse necking effect is similar to what can be experienced during superplastic deformation. However, when comparing the presence of a diffuse neck in this research, electrical pulsing does not create as significant of a diffuse neck as superplastic deformation. Electrical pulsing has the potential to be more efficient than traditional methods of incremental forming since the deformation process is never interrupted. Overall, with the greater elongation and lower stress, the aluminum can be deformed quicker, easier, and to a greater extent than is currently possible.

INTRODUCTION
When manufacturing metallic parts from sheet metal, there is a limit to which the blanks can be deformed prior to fracture. This limit is primarily controlled by properties such as the strength, strain hardening coefficient, and formability of the metal. For some applications which require complex parts, such as the automotive and aircraft industries, several simpler parts must first be constructed and then assembled using attachment methods such as rivets, screws, or welds. Depending on the complexity of the part, this traditional way of manufacturing can be time consuming and extremely costly to the manufacturer. In order to address this problem, a manufacturing process must be developed which allows complex parts to be formed from a single sheet metal blank, rather than assembling numerous smaller pieces.

Traditionally, a metal's formability is increased by plastically deforming the metallic blanks at an elevated temperature. However, there are several notable drawbacks to this, such as increased adhesion between the specimens and dies, reduced effects of lubrication, and decreased die strength. Overcoming these drawbacks usually significantly increases the part cost associated with equipment, energy, and time.

Recently, a metallic deformation method, known as incremental forming, was introduced where the blank is deformed in steps, with a minor heat-treatment performed after each step [1]. Although this type of forming is effective and shows beneficial deformation effects, it is also time consuming and introduces possible quality issues since the deformation process must be stopped and the part repeatedly removed and refixtured. Therefore, if an alternative to both hot working and incremental forming can be developed, there is the potential to significantly improve process efficiency by decreasing both the production time and manufacturing cost.

Beginning in the late 1960's, researchers began investigating how electricity affects the material properties of metals. As this research has progressed, it has been found that a vast number of material properties can be altered using electricity. In 1969, Troitskii discovered that pulsed electricity lowers the flow stress within certain metals [2]. In 1988, Xu et al. published a document demonstrating that a continuous electric current within specific materials can increase the material's recrystallization rates and grain size [3]. Moreover, Chen et al. discovered a connection between electrical flow and the formation of intermetallic compounds [4, 5]. From studies conducted by Conrad, it was shown that plasticity and the phase transformation of various metals and ceramics are affected by very short duration, high current density electrical pulses [6 - 8]. Recently in 2007, Andrawes et al. demonstrated the stress strain behavior of 6061 Aluminum Alloy can be altered using elevated amounts of DC current [9]. Also, Heigel et al. reported on the effects that DC current had within the microstructure of 6061 Aluminum Alloy [10].

In 2007, the effect of a continuous DC current on the mechanical properties of numerous metals while in tension was explored by Ross et al. [11]. Additionally, Perkins et al. investigated DC current's effect on metals undergoing an upsetting process [12]. These two investigations of continuous DC current proved that the presence of the continuous current during plastic tensile deformation reduced the flow stress within the material. However, while the study by Ross et al. showed the formability of the metals was increased during compressive deformation, the study by Perkins et al. found that the continuously applied electricity reduced the maximum achievable elongation when applied during tensile deformation (thus having a negative impact on the metals when the DC electricity was continuously applied during tensile deformation).

ELECTRIC PULSING THEORY AND PREVIOUS WORK

Electrical current pertains to electrons flowing through a material. All materials have a set resistance to electron flow due to their bonding, atomic spacing, and atomic structure. Point defects, dislocations, and interfacial defects (grain boundaries, cracks, voids, etc.) within a material can increase a material's resistance to electron flow even more. As plastic deformation takes place, the dislocations moving through the material also experience resistance when moving across grain boundaries, cracks, voids, impurity atoms, and other dislocations. When a material is loaded, dislocations move through these obstacles by changing direction, bending, sliding, or bowing. As the amount of cold-work is increased, the resistance to dislocation motion also increases; thereby increasing the required flow stress. However, if the dislocations are able to move through a material with less resistance, the material will become easier to deform. Therefore, the principle behind electrical pulsing is to modify the material's properties such that the dislocations within the material are able to move as freely as possible. By doing so, the material becomes temporarily weaker, minimizing the force/energy that is required to fabricate the part. A second goal of the electrical pulsing is to increase the maximum achievable elongation of the material prior to fracture. Increasing this elongation has several potential benefits, such as allowing more complex parts to be fabricated using the material, decreasing the weight/material usage required for the part, or reducing the number of individual parts that must be created in order to create complex part shapes.

Previous studies have indicated that, when continuous DC current is applied to a part during tensile or compressive deformation, the required flow stress is reduced [11, 12]. However, the effect of the continuous current on the maximum achievable elongation of the part was significantly different for compressive and tensile loading. When performing compression-based deformation, it was found that the application of a continuous current dramatically increased the material's deformability. This was not true when performing tensile-based deformation, however. When continuous electricity was applied during tensile-based deformation it was noted that the deformability of the material decreased.

In subsequent studies, however, it was discovered that, when a pulsed current (rather than continuous) was applied during tensile deformation, the maximum achievable elongation was increased (rather than decreased as was true for continuous). In a recent study conducted by Roth et al., the effects of a pulsed DC current on 5754 Aluminum Alloy, a widely-used alloy for body panels in the automotive industry, were investigated [13]. This research involved developing an optimal pulsing parameter in order to minimize the flow stress and maximize the material's overall achievable elongation, thereby placing the material into its most-workable state. The current density at which the specimens were pulsed was held constant at 90 A/mm^2, while the pulse duration and period between pulses were varied. The electric pulsing lead to extreme increases in elongation over non-pulsed baseline tests as shown in Figure 1, where the pulsing period was steadily decreased. About a 400% increase in elongation and a notable decrease in flow stress due to electrical pulsing can be seen from the figure.

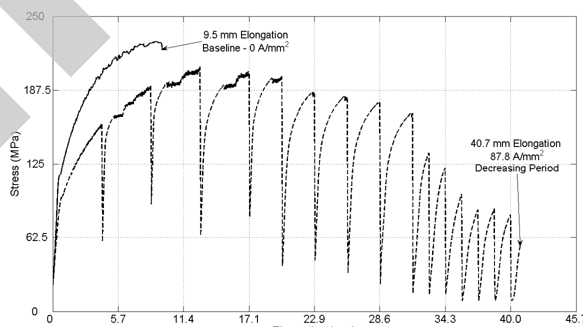

FIGURE 1 – 5754 ALUMINUM WITH DECREASING PULSE PERIOD

Unlike the 5754 Aluminum research, this research does not focus on determining an optimal, or best, parameter set for the 5052 and 5083 Aluminum alloys that are examined herein. Instead, the purpose of this research is to explore the effects of a pulsed DC current on various heat-treatments of these materials. More specifically, the research discussed herein examines if the effectiveness of the pulsed electricity is altered by the aluminum's heat-treatment.

To examine this possibility, it is important to use the same combination of pulse parameters on each heat-treatment (two different combinations will be examined as a part of this study). However, it should be noted that, while using the same pulse parameters for each heat-treatment improves the ability to perform a cross-comparison of the electricity's effectiveness, it prevents optimal parameters from being employed to enhance the workability of each alloy/heat-treatment combination. Therefore, greater improvements are achievable for each combination of alloy and heat-treatment if a separate optimization of the parameters is performed.

EXPERIMENTAL SETUP

To reduce the effect of stock variability, all of the material for each alloy originally came from the same sheet stock. This original stock was sectioned into the necessary sizes and then heat-treated to the desired specification. Subsequent to performing the required heat-treatments, dogbone test specimens were created for testing purposes. The dogbone specimens were fabricated by initially shearing the sub-sheets from each heat-treatment into rectangular shapes. When performing the shearing operation, the width of the rectangles was intentionally oversized. After creating the rectangular blanks, the specimens were machined on all sides in order to remove any unintentional effects from the shearing operation.

When machining (milling) the dogbone specimens for this testing it is important to maintain tight tolerances on all dimensions, otherwise the current density will vary slightly, introducing testing variability. To reduce this variability, the dimensions on all of the dogbones produced for this study were held to a tolerance of less then 12.5 µm (0.0005").

For the tensile testing described herein, a Tinius Olsen Super "L" Universal Testing Machine was used to elongate aluminum alloy dogbone test specimens. The electric pulses were created using a Lincoln R35 Arc Welder with a variable voltage output and a pulse controller. In addition, a variable, thermally cooled resistor was used to control the magnitude of the electrical pulses. The test fixtures consisted of hardened steel clamps, Haysite Reinforced Polyester, and PVC tubing. The hardened steel mounts held the aluminum dogbones in place during testing. The polyester and PVC tubing were inserted between the steel clamps and the Tinius Olsen machine to isolate the electricity from the testing equipment, thus sending the current through the dogbone specimens only. The setup used for this experiment is the same setup used in the 5754 Aluminum Alloy research as discussed previously. This setup is shown in Figure 2.

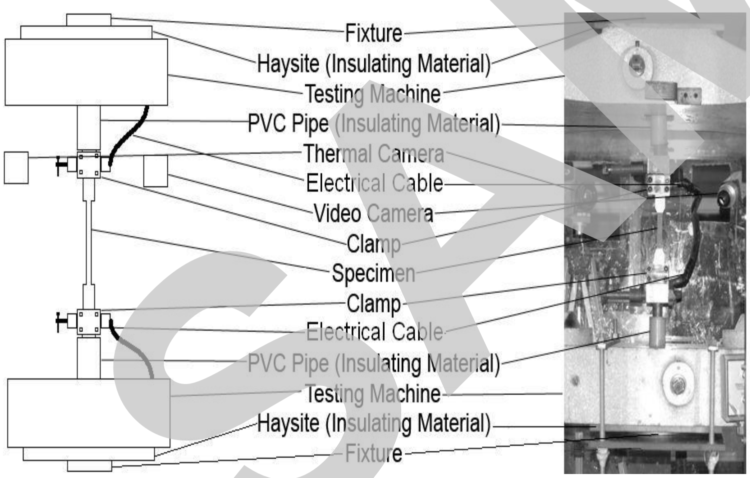

FIGURE 2 – EXPERIMENTAL SETUP

The current flowing from the welder was monitored using an Omega HHM592D Digital Clamp-on Ammeter. PC-based Tinius Olsen Navigator software was used to control the universal testing machine and to continuously obtain the force vs. position data throughout each test. The entire circuit schematic can be viewed in Figure 3. Using the force vs. position data and each specimen's original cross-sectional area measurements, engineering stress vs. elongation plots were generated. Elongation was used instead of strain due to the presence of a diffuse neck, which was the result of non-uniform strain. Strain proves to be an incorrect parameter to use for graphing since it does not stay constant throughout the entire test region of the specimen [14].

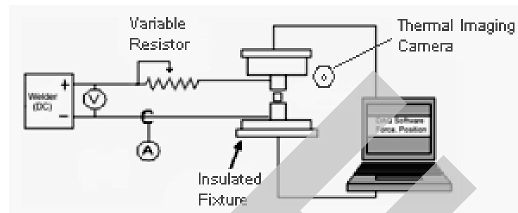

FIGURE 3 – CIRCUIT SCHEMATIC

To observe possible thermal effects, a FLIR infra-red thermal imaging camera (ThermoVision A20m) continuously monitored the temperature profile of the specimen throughout the entire length of each test. High temperature black paint was applied to the back of each test specimen (side facing the thermal imaging camera) to stabilize the sample's emissivity and to allow for more accurate temperature data. Although the temperature data was not directly used in this research, the temperature was monitored to ensure the specimens did not exceed the aluminum's maximum operating temperature range.

Due to the non-uniform strain profile that is created within each specimen during the testing (discussed in the results section), a grid of displacement/strain circles were acid etched on the front of the specimens (side opposing the thermal imaging camera) prior to testing. These grids will be used to analyze the displacement profile along the "long-axis" of each specimen after fracture. An example of the displacement grid is shown below in Figure 4.

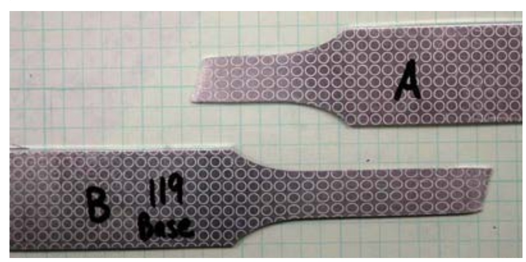

FIGURE 4 – DISPLACEMENT GRID

The testing procedure consisted of elongating the aluminum dogbone specimens at a constant platen rate of 2.54 mm/min (0.1 in/min) until fracture, while the specimens were periodically pulsed with a specific amplitude of electrical current applied over a set duration. It is important to note that the electrical pulses were applied to the specimens during the elongation process, without interrupting the deformation. When viewing the engineering stress-elongation graphs presented in the Results section, the electrical pulses are responsible for the steep vertical drops (corresponding to a sudden decrease in the flow stress required for the deformation). In order to examine the effect of the heat-treatment on the effectiveness of the electrical pulsing, two different alloys of aluminum, with three different heat-treatment conditions, are examined in this research. Table 1 lists the alloys, along with the heat-treatments examined.

TABLE 1 - ALLOYS AND HEAT TREATMENT CONDITIONS

Alloys	Heat-Treatment Conditions
5052-H32	As-Is 398°C for 10 minutes 510°C for 6 hours
5083-H32	As-Is 398°C for 10 minutes 510°C for 6 hours

In order to more exactly determine the effect of the electrical pulsing on each alloy/heat-treatment combination, two different sets of pulse parameters were employed, as listed in Table 2. In these parameter sets, the pulse duration was held constant as the current density (magnitude) and the pulsing period were changed. Figure 5 depicts the electrical pulsing pattern used for this research. The parameters used in this research were chosen based on preliminary testing using a few of the material/heat-treatment combinations to determine the overall impact that they had for all of the material combinations. Therefore, while the parameters were consistenly beneficial, they do not represent the optimal parameters for any particular combination. To achieve optimal results, unique parameter sets would need to be employed for each alloy/heat-treatment combination. For this research, universal parameter sets were employed in order to allow for a cross-comparison of the effectiveness of the electricity between all combinations.

TABLE 2 - ELECTRICAL PULSING PARAMETERS

Parameter Set	Current Density (A/mm^2)	Duration (Seconds)	Period (Seconds)
1	90	1	60
2	60	1	30

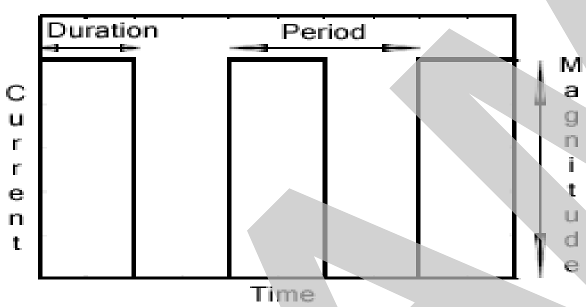

FIGURE 5 – ELECTRICAL PULSING PATTERN

To verify the repeatability of the results, five specimens were tested for each aluminum alloy/heat-treatment/parameter-set combination. Also, to provide a means of establishing the electricity's effect, multiple baseline tests (where electricity was not applied) were conducted for each heat-treatment of the two aluminum alloys examined. While multiple tests were run for each set of conditions, to ease the ability to visualize the effect of the pulsed electricity for each engineering stress-elongation diagram within the Results section, only a single representative curve is plotted for each condition. Thus, each plot only contains one pulsed test and its respective baseline test for each specific aluminum alloy/heat-treatment/parameter-set combination. However, while not shown, all five tests were examined for each combination to verify satisfactory repeatability between the tests. As with the engineering stress vs. elongation plots, the displacement analysis plots also only depict one representative test for each aluminum alloy/heat-treatment/parameter-set combination. As was true for the stress-elongation data, once again, sufficient repeatability was found between the various specimens deformed under the same conditions.

RESULTS

In the following sub-sections, the effects of Parameter Set 1 and Parameter Set 2 are cross-compared to each other and to the baseline material for each aluminum alloy/heat-treatment combination. In addition, the elongation along the specimen's axial length for each combination using Parameter Set 1 and 2 are cross-compared. These axial elongations are also compared to the baseline's elongation for the respective alloy/heat-treatment combination in order to determine each parameter set's effect on the material's axial elongation profile. These axial elongations are analyzed by measuring the increase in length of each strain circle on the grid that was acid etched on one side of the aluminum test specimens. The results are used to compare the specimen's "long-axis" deformation due to Parameter Set 1, Parameter Set 2, and the baseline.

From visual inspection of the tested specimens in this research, it can be noted that the testing region of most pulsed specimens displayed a diffuse necking effect. This diffuse neck is similar to, although less sever, the diffuse neck frequently seen with superplastic forming [15]. The neck generated when deforming with electrical pulses, shown for one of the specimens in Figure 6 for reference, corresponds to a non-uniform displacement profile along the test specimen. Note that, although the figure shows that the displacement grid is applied to the entire specimen, the testing region (fillet to fillet) is the only region of concern. Thus, the axial displacement profiles that will be presented only focus on this region. In addition to the local axial displacement measurements, the overall elongation (between fillets) is measured and presented for each set of conditions.

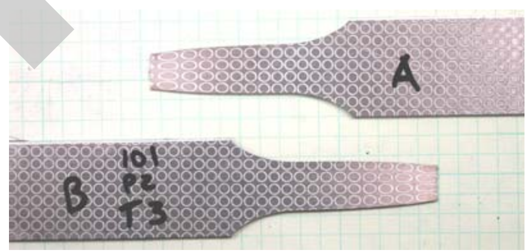

FIGURE 6 – PULSED SPECIMEN WITH DIFFUSED NECK

As previously mentioned, for both alloys, the pulsed electricity's effect on three different heat-treatments is examined using two different parameter sets. For each alloy, the first set that is presented corresponds to the "As Is" stock state (i.e., the state of the stock material without secondary heat-treatments). The second heat-treatment presented for each alloy corresponds to the secondary treatment of the "As Is" material at 398°C for 10 minutes. The final heat-treatment presented for each alloy involves the secondary treatment of the "As Is" material at 510°C for 6 hours.

Effect on 5052-H32 Aluminum Alloy

For the 5052 Aluminum alloy examined as a part of this research, the "As Is" state corresponds to 5052-H32.

5052-"As Is": As previously mentioned, in order to establish the effect of the pulsed electricity on the mechanical properties of the 5052-"As Is", five repetitions of each test condition were conducted.

While slight variability was found to exist between the repetitions, this variability was deemed negligible for the purposes of this analysis.

The representative curves of the engineering stress versus elongation behavior of the 5052-“As Is” material, when deformed while applying the pulsed current conditions associated with Parameter Set 1 and Parameter Set 2, are shown in Figures 7 and 8 respectively. To improve the ability to visualize the effect of the pulsed current on the material’s behavior, the baseline stress-elongation behavior of the material is also plotted in the figures. When interpreting these images, the sharp drop in the material’s flow stress (the stress to continue deformation at any given elongation) corresponds to the application of each individual pulse of electricity.

When comparing the average elongation of the 5052-“As Is” material from deforming while applying the conditions associated with Parameter Set 1 (7.1 mm) to the average baseline deformation (4.6 mm), an increase of 54.3% is observed (Figure 7). Note that, when computing this percent increase (and for all subsequent calculations), the average elongation for each condition are used (i.e., the average elongation from all of the baseline tests is compared to the average elongation from all of the 5052 As-Is specimens deformed using Parameter Set 1). In addition, the flow stress also decreased due to the application of the pulsed electricity. To this end, each pulse of electricity results in a material response that is similar to an instantaneous anneal of the material.

Likewise, when applying the conditions associated with Parameter Set 2 (Figure 8), an increase in the overall elongation of the material is also observed in comparison to the baseline behavior. Unfortunately, the improvement in the material’s overall elongation while pulsed under Parameter Set 2 is significantly reduced in comparison to Parameter Set 1; yielding an average elongation from using Parameter Set 2 of only 4.7 mm, a 2.2% elongation increase from baseline. Not surprisingly, when applying the conditions of Parameter Set 2, the flow stress is not lowered to the same extent as occurred when pulsing under the conditions of Parameter Set 1.

To provide a more detailed analysis of the electricity’s effect on the material’s axial elongation, the displacement grid profiles of the specimens are also examined. The 5052-“As Is” displacement profile for Parameter Set 1, Parameter Set 2, and its respective baseline are all depicted in Figure 9. As can be seen, the baseline plot shows a minimal necking region (corresponding to the peaks left of center). However, it also reveals an inconsistent displacement profile (note the significant variations in strain levels throughout the testing region in the figure) compared to the other, more consistent, 5052 Aluminum Alloy baseline displacement profiles (to be presented in the following sub-sections).

When deforming the specimens with the pulsed Parameter Set 1, however, a significant diffuse neck region is found to exist (i.e., the degree of elongation is not constant along the profile but instead consistently increases as the neck is approached). An additional observation regarding the necking event is that, while the point necking was located for the baseline specimens at approximately one-third of the testing length, when pulse Parameter Set 1 is applied, the neck consistently occurred at the specimen’s midpoint. This occurs due to the conductive influence of the fixtures causing the center of the specimen to increase in temperature the most due to Joule heating. For Parameter Set 2, however, only a minimal diffuse neck is observed and the fracture event once again occurred at approximately one-third along the testing region length. This similarity between the baseline behavior and that for Parameter Set 2 is not unexpected given the minimal effect on the material’s behavior due to the pulsing under the conditions of Parameter Set 2.

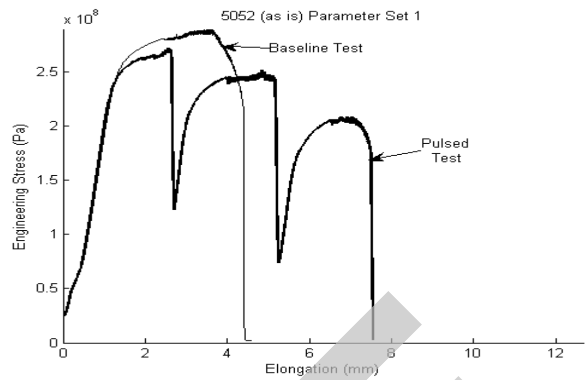

FIGURE 7 - 5052 - AS IS - PARAMETER SET 1

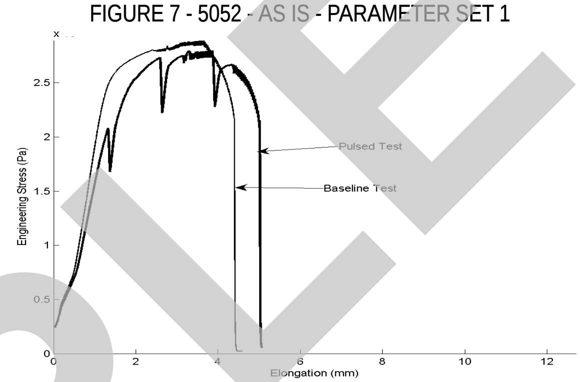

FIGURE 8 - 5052 - AS IS - PARAMETER SET 2

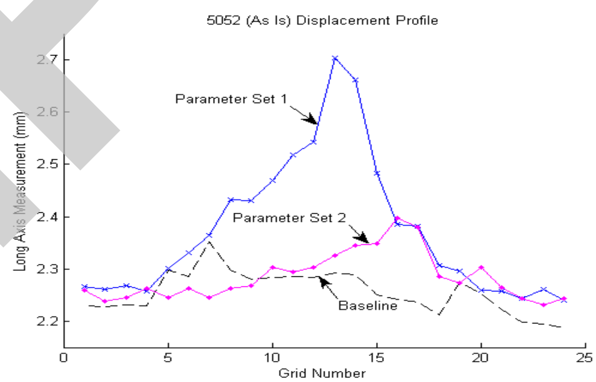

FIGURE 9 - 5052 - AS IS - DISPLACEMENT ANALYSIS

5052-After 398°C for 10 minutes: The next series of tests were run after heat-treating the aluminum at 398°C for 10 minutes. The effect of the pulsing under Parameter Set 1 and Parameter Set 2 are shown in Figures 10 and 11 respectively. Once again, the baseline data is plotted on both graphs along with a representative pulsed test to ease comparison. In examining the two graphs, it is apparent that the pulsed electricity had a more consistent effect (less variability between repetitions) on the 5052 398°C material, both for the first and second set of pulse parameters. As will be shown later, this was also true for the heat-treatment at 510°C for 6 hours.

For the 398°C series of tests (Figures 10 and 11), the overall baseline elongation was 18.4 mm. As was done previously for the “As Is” stock tests, this baseline will be used to determine the amount by which the pulsed electricity altered the elongation of the material. For the samples tested using Parameter Set 1 (Figure 10), the overall elongation (28.8 mm) corresponds to a 56.5% increase in comparison to the baseline's elongation and also decreases the engineering flow stress. For the tests pulsed under Parameter Set 2 (Figure 11), the overall elongation (27.8 mm), resulted in an increase of 51.1% compared to the same respective baseline test. As was the case with Parameter Set 1, this parameter also decreased the engineering flow stress a notable amount.

When considering both achievable elongation increases, along with decreases in flow stress, it is apparent that both pulse conditions had beneficial effects on the 5052 398°C material. Both parameter-sets achieved roughly the same amount of elongation, with Parameter Set 1 proving to be slightly better. Furthermore, although both parameter sets decreased the flow stress, Parameter Set 1, again, evidencing a greater decrease in flow stress than Parameter Set 2 indicating that the magnitude of the current played a greater role than the pulsing frequency in determining the peak flow stress reached between pulses for these two particular sets of conditions. In addition, each pulse caused a greater decrease in the stress (note the extent of the "drop-off" on the graphs each time the current was applied) for Parameter Set 1. This is expected considering the greater magnitude of the current used for Parameter Set 1.

When viewing the displacement profile in Figure 12, it becomes apparent that the electric pulsing with both parameters causes a diffuse neck within the specimen. The baseline profile displaced consistently with minimal necking near the point of fracture. The baseline displacement profile for this heat-treatment proved to be more consistent than the "As Is" profile (notice less variability in strain over the testing region).

The specimens pulsed under conditions of Parameter Sets 1 and 2, however, both elongated non-uniformly over the entire testing region (fillet to fillet). The specimens pulsed under Parameter Set 2's conditions displayed a slightly longer diffused neck up to fracture than the specimens pulsed under Parameter Set 1's conditions. One possible reason for this is that, since the material's width was considerably decreased by this point in the test, the lower magnitude pulses of Parameter Set 2 may have been more beneficial than the higher magnitude pulses of Parameter Set 1. More specifically, the greater magnitudes of Parameter Set 1 may have caused premature failure of the specimen due to highly localized heating within this narrowed region. Also of note, both pulsed tests fractured at approximately the center of the testing region, while the un-pulsed baseline test fractured asymmetrically (slightly left of center). Therefore, while pulsing the specimens, the high temperatures reached in this central area lead to consistent fracture at this location for all tests conducted at this material/heat-treatment combination.

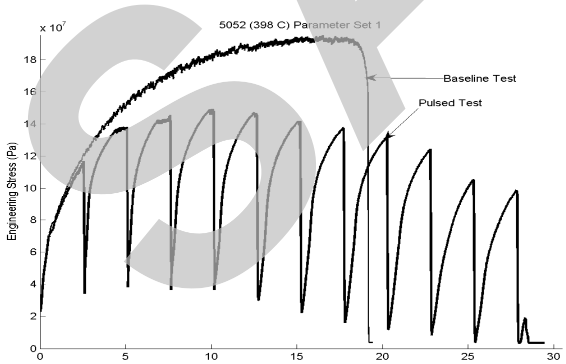

FIGURE 10 - 5052 - 398°C - PARAMETER SET 1

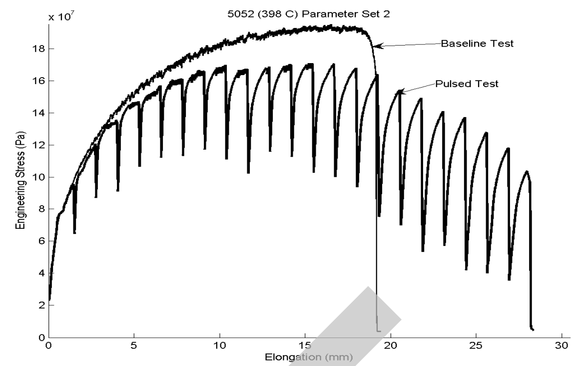

FIGURE 11 - 5052 - 398°C - PARAMETER SET 2

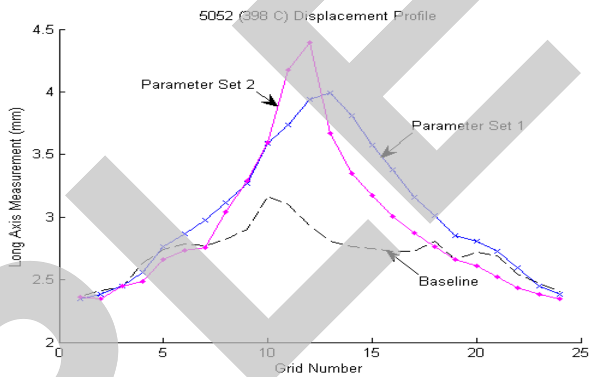

FIGURE 12 – 5052 - 398°C – DISPLACEMENT ANALYSIS

5052-After 510°C for 6 hours: The final series of 5052 tests were run after heat-treating the original aluminum "As-Is" sheet stock at 510°C for 6 hours. Once again, the overall elongation of the baseline specimens and the pulsed tests are used for comparison purposes. From this, when Parameter Set 1 was used (Figure 13), the overall elongation of 27.8 mm represents an increase in this aluminum alloy's elongation by about 47.1% with respect to the baseline elongation (18.9 mm). Furthermore, with the use of Parameter Set 2 conditions (Figure 14), a 57.1% increase from beyond the baseline elongation was calculated (the overall elongation associated with the tests conducted under the conditions of Parameter Set 2 was 29.7 mm).

Overall, both Parameter Set 1 and Parameter Set 2 had a greater effect on the 5052 Aluminum's elongation when applied to the heat-treatment at 510°C for 6 hours than was the case for either of the two previous heat-treatments. Moreover, for this heat treatment, the conditions of Parameter Set 2 resulted in a greater improvement in the elongation than was found with the conditions of Parameter Set 1. However, once again, Parameter Set 1 resulted in a greater decrease in the material's peak flow stress between pulses than Parameter Set 2 and also resulted in greater "drop-offs".

From Figure 15, the same diffuse necking effect as experienced in the 5052 398°C specimens was also present in the specimens heat-treated at 510°C for 6 hours. Once again, the baseline profile displayed relatively uniform displacement throughout most of the tested region. Both pulsed specimens proved to have similar displacement profiles over most of the testing region. In this case, Parameter Set 2 depicted an even greater diffuse necking effect compared to Parameter Set 1 than was the case for the 398°C heat-treated alloy.

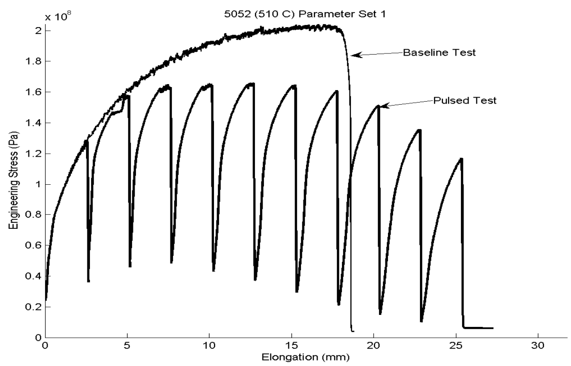

FIGURE 13 - 5052 - 510°C - PARAMETER SET 1

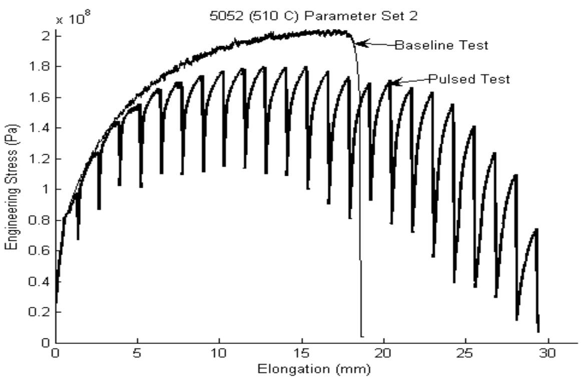

FIGURE 14 - 5052 - 510°C - PARAMETER SET 2

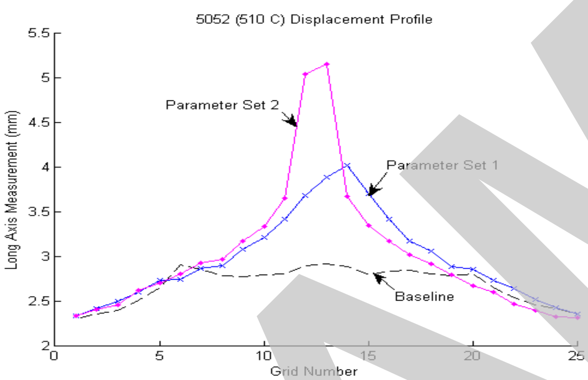

FIGURE 15 – 5052 - 510°C – DISPLACEMENT ANALYSIS

5052-Summary: As shown, with respect to the material's maximum achievable elongation, Parameter Set 1 proved to be the most successful when applied to the 5052-"As Is" stock specimens and the 5052-398°C for 10 min. specimens while Parameter Set 2 yielded the best results when applied to the 5052-510°C for 6 hours specimens. Furthermore, for the 5052 Alloy, the pulsed electricity's effect increased as the heat-treatment temperature and time increased. With respect to the required engineering flow stress, however, a more consistent effect was evidenced in so far as, for all of the tests conducted on the three heat-treatments of the 5052 Aluminum Alloy, the peak engineering flow stress was reduced to a greater extent when the conditions associated with Parameter Set 1 were used (demonstrating that the pulse magnitude had a greater effect than the pulse frequency for these two sets of conditions). This result is somewhat unexpected since Parameter Set 2 called for pulses twice as frequent as that of Parameter Set 1, resulting in a greater percentage of the testing time over which the electricity was actually applied to the specimen. Finally, as expected, the higher magnitude of the current applied by the conditions of Parameter Set 1 resulted in a greater "drop-off" in the stress when the pulse was applied than was occurred due to Parameter Set 2's conditions.

Comparing all three heat-treatments of the 5052 Aluminum Alloy, the overall effect of Parameter Sets 1 and 2 created a diffuse neck within the tested region of the specimens. Parameter Set 2 caused a greater diffuse neck for heat-treatments of 398°C and 510°C, leading to belief that pulsing frequency determined the extent of the diffuse neck. This was not the case for the "As Is" material, where Parameter Set 1 created a significantly larger diffuse neck. In most cases, excluding the 5052-"As Is" Parameter Set 2 pulsed specimens, the electrical pulsing caused the ultimate fracture to occur at the middle of the testing region, while the baseline fractures occurred asymmetrical. Once again, this may have been due to the absence of thermal sinks near the middle of each specimen's testing region.

Effect on 5083-H32 Aluminum Alloy

As was true for the 5052 Alloy, the first 5083 Aluminum Alloy heat-treatment that will be examined corresponds to the "As Is" stock state of the material (i.e., the state of the stock material without secondary heat-treatments), followed by the 398°C for 10 minutes series and, finally, the 510°C for 6 hours series of tests. The 5083-"As Is" state corresponds to 5083-H32.

5083-"As Is": As was done previously for the 5052 Aluminum Alloy tests, the plots will consist of a baseline test along with a pulsed test representative of the five tests conducted for each combination, as seen in Figures 16 and 17. The average baseline elongation was determined to be 9.6 mm for the "As Is" material. The results of applying the conditions of Parameter Set 1 are shown in Figure 16. As can be seen, the application of the pulsed electricity significantly increased the elongation of the specimens with an overall elongation of 17.3 mm. This overall elongation corresponds to an increase of 80.2% over the respective baseline elongation. Moreover, the effects associated with applying Parameter Set 2 (Figure 17) to this material were even more promising with an overall elongation of 18.3 mm. This elongation corresponds to a percent increase of 90.6%.

Therefore, while the pulsed Parameter Set 2 conditions did not significantly improve the 5052-"As Is" specimens, it had a significant effect on this alloy. In addition, while both parameter sets once again were found to reduce the peak flow stress between pulses, for this alloy/heat-treatment combination, Parameter Set 2 proved to reduce the engineering stress more rapidly and effectively than Parameter Set 1 (a different result than that found with the 5052 Alloy). This leads to the conclusion that the pulse frequency played a greater role in reducing the flow stress rather than the pulse magnitude (the magnitude was the greater factor with the 5052 Aluminum Alloy). One similarity between the effects of the parameters on the two alloys, however, is that, Parameter Set 1 provided a greater "drop-off", as expected due to the larger current density per pulse.

The displacement analysis for this alloy is also conducted in the same manner as the 5052 Aluminum Alloy. Each profile plot in the displacement analysis figure is representative of the five specimens tested for each material/heat-treatment/parameter-set combination. The 5083-"As Is" displacement profiles in Figure 18 show a uniformly-displaced baseline test, along with diffused necks resulting from both pulsed parameter set tests. Unlike the 5052-"As Is"

Aluminum's baseline profile, this baseline displacement profile was more consistent throughout the testing region. Parameter Set 2 caused a greater diffused neck and both parameter sets caused ultimate fracture in the center of the test region.

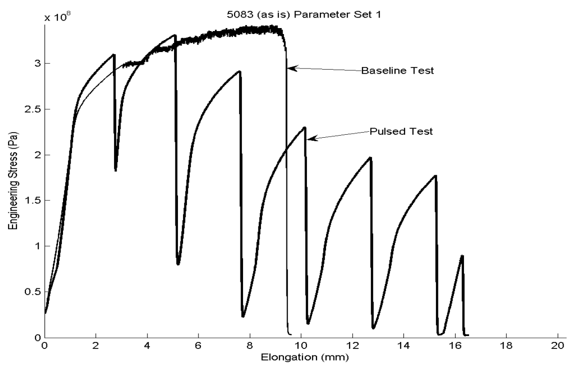

FIGURE 16 - 5083 - AS IS - PARAMETER SET 1

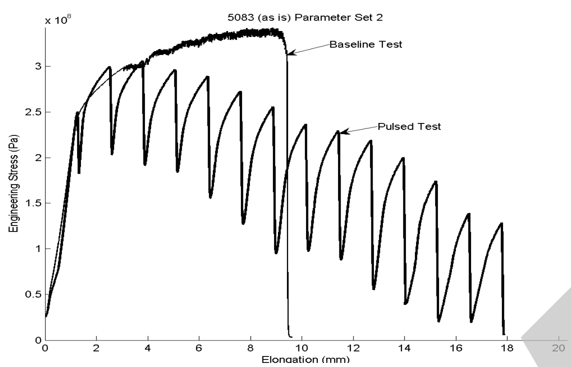

FIGURE 17 – 5083 – AS IS – PARAMETER SET 2

FIGURE 18 – 5083 – AS IS – DISPLACEMENT ANALYSIS

5083-After 398°C for 10 minutes: Figures 19 and 20 clearly show that both parameters extended the elongation of the 5083-398°C for 10 min. specimens past the comparable baseline elongation of 18.3 mm. More specifically, the overall elongation for Parameter Set 1 (Figure 19) was 22.1 mm, a 20.8% increase in elongation from the respective baseline. The conditions associated with Parameter Set 2 (Figure 20) were more successful with a 41.5% increase in elongation (overall elongation was 25.9 mm). It is of note that, while the total elongation of the specimens for both parameter sets is greater than the "As Is" elongations, the percent improvement is less after the heat-treatment. This decrease in effectiveness after treatment is the opposite of that exhibited by the 5052 Alloy.

As was the case with the 5083-"As Is" stock material, both parameter sets once again reduced the peak flow stress between pulses, for this alloy/heat-treatment combination. Moreover, Parameter Set 2 once again proved to reduce the engineering stress more rapidly and effectively than Parameter Set 1 for this alloy. This result seems to indicate that the pulsing frequency played a greater role than the magnitude of the current in determining the peak engineering flow stress reached between pulses for these two particular sets of conditions. Parameter Set 1, however, once again provided the greatest "drop-off" in stress while the electricity was flowing through the material during deformation. Moreover, at the higher elongations, this "drop-off" nearly reached zero stress as seen in Figure 19, a remarkable stress-state considering the continuous on-going deformation of the specimen while the pulse was applied.

The displacement profiles of the 5083 398°C Aluminum Alloy are similar to the displacement profiles of the same "As Is" Aluminum Alloy. In Figure 21, the baseline profile is somewhat uniform compared to the displacement profiles of the two pulsed parameters. From the figure, it is apparent that the electrical pulsing used in both parameter sets resulted in the specimen having a diffuse neck. As was the case with the "As Is" material, the electrical pulsing of Parameter Set 2 caused a greater diffuse neck compared to Parameter Set 1. Both parameter sets ensured the fracture occurred in the middle of the test region.

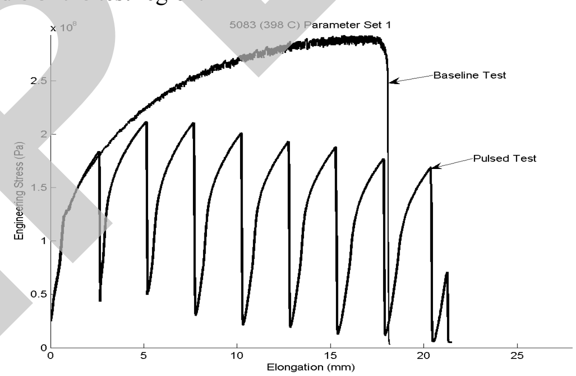

FIGURE 19 - 5083 - 398°C - PARAMETER SET 1

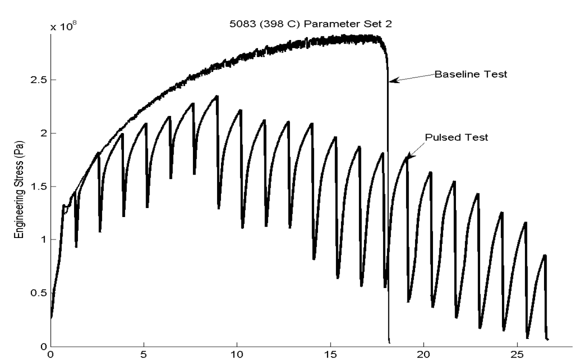

FIGURE 20 – 5083 - 398°C – PARAMETER SET 2

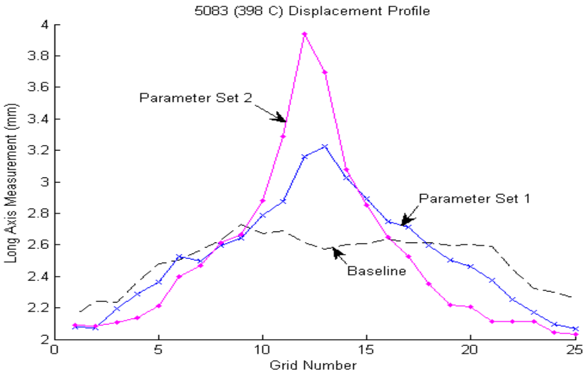

FIGURE 21 - 5083 - 398°C - DISPLACEMENT ANALYSIS

5083-After 510°C for 6 hours: The results of applying the conditions associated with pulse Parameter Set 1 and 2 to the 5083-H321 Aluminum heat-treated at 510°C for 6 hours are shown in Figures 22 and 23, respectively. As was done with the other series, the baselines and the pulsed tests are compared. Once again, the 5083-510°C for 6 hours Aluminum's elongation was increased due to the conditions applied by both parameter sets. For this alloy/heat-treatment combination, the overall baseline elongation is 18.5 mm.

By comparing Figures 22 and 23, it can be seen that, for this alloy/heat-treatment, Parameter Set 1 was once again less effective at increasing the material's maximum achievable elongation (as was the case with all of the other heat-treatments for this alloy). More specifically, for Parameter Set 1, the pulsed electricity resulted in an overall elongation of 24.3 mm, an increase by 31.4% over the baseline distance. Similarly, for Parameter Set 2, the application of the pulsed electricity during deformation resulted in an overall elongation of 27.6 mm, a 49.2% increase over the comparable baseline.

When examining the effect of the pulsed conditions on the specimen's peak engineering flow stress, however, a slightly different result is found for this heat-treatment. In this case, the conditions of Parameter Set 1 initially decrease this stress to a greater extent. However, as the elongation is increased, the conditions of Parameter Set 2 begin to have a greater effect on the stress, ultimately resulting in Parameter Set 2 finishing with the lower peak stress of the two. Also of note, once again the Parameter Set 1 causes a greater "drop-off" in stress while the electricity is applied. Furthermore, as was true with the 5083 398°C Aluminum specimens, at higher elongations this "drop-off" nearly reaches a state of zero stress (refer to Figure 22), irrespective of the on-going deformation of the specimen during the pulsing.

The displacement analysis for the 5083 510°C Aluminum Alloy can be found in Figure 24. Just like the other heat-treatment/parameter-set combinations for this alloy, a diffuse neck is present in both electrically-pulsed tests, while the baseline displayed no sign of a diffuse neck. Moreover, Parameter Set 2 registered a greater necking effect, leading to the conclusion that the frequency of the pulses had a greater effect on the diffuse neck than the magnitude of the current.

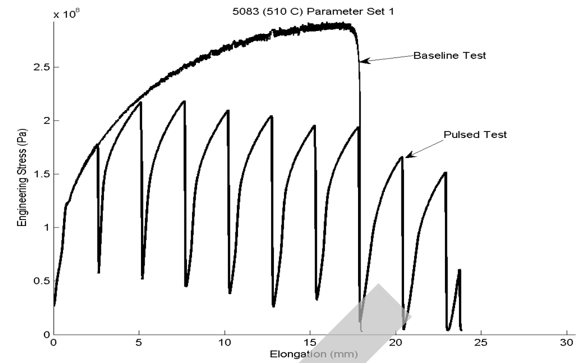

FIGURE 22 – 5083 – 510°C – PARAMETER SET 1

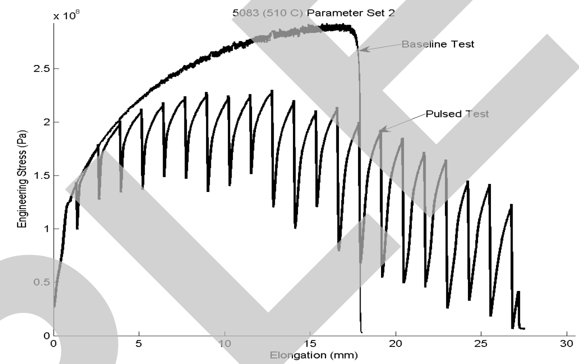

FIGURE 23 – 5083 - 510°C – PARAMETER SET 2

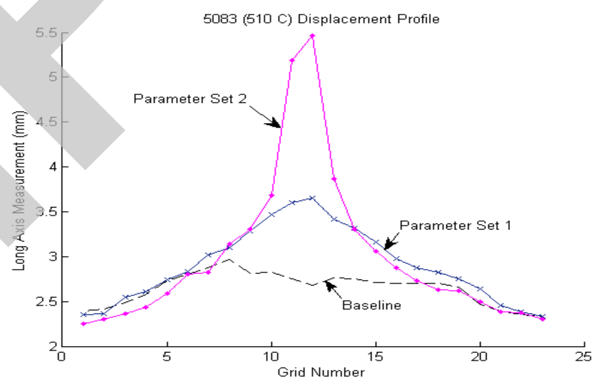

FIGURE 24 - 5083 - 510°C - DISPLACEMENT ANALYSIS

5083-Summary: As was true with the 5052 Aluminum Alloy, for all of the 5083 heat-treatments, both parameter-sets resulted in an increase in the maximum achievable elongation of the alloy. However, unlike with the 5052 Alloy tests, for this alloy, Parameter Set 2 consistently reached greater elongations than Parameter Set 1. This indicates this alloy is more sensitive to frequency than magnitude. Also, Parameter Set 2 decreased the peak engineering flow stress between pulses to a greater extent than Parameter Set 1 (a result also opposite than found for the 5052 Alloy). Both alloys, however, exhibited a greater "drop-off" in the stress due to the pulses associated with Parameter Set 1. Moreover, in some cases, this "drop-off" nearly reached a stress-state of zero, even though the specimens were still undergoing deformation during the pulse.

All of the pulsed specimens for each heat-treatment/parameter-set combination for the 5083 Aluminum Alloy display a diffuse neck in their respective test region. Baseline specimens show minimal or no diffuse necking in their test regions. The conditions of Parameter Set 2 consistently produced a greater diffuse necking effect on the specimens than the conditions of Parameter Set 1. This concludes that the more frequent, slightly less magnitude pulses of Parameter Set 2 are more effective in producing a diffuse neck than the shorter, greater magnitude pulses of Parameter Set 1.

CONCLUSION

As was shown, the effectiveness of the pulsed electricity is dependent on both the alloy and its heat-treatment. The material that obtained the most increase in formability due to the electric pulses was the 5083 Aluminum Alloy. For this material, not only was the elongation increased by the greatest percentage, the engineering stress was reduced by the greatest amount. Parameter Set 2, with more pulses of slightly smaller magnitude, worked the best in conjunction with this material, for all of the heat-treatments.

The 5052 Aluminum Alloy, although not as successful as the 5083 material, did illustrate signs of formability improvement from the electric pulsing. For this alloy, Parameter Set 1 was more successful with the “As Is” and 398°C heat-treatments, but Parameter Set 2 proved more successful with the 510°C heat-treatment. However, on average, Parameter Set 1 lowered the engineering stress to a greater extent than Parameter Set 2. The engineering stress of the 5052-“As Is” material was the only case whose stress was not significantly affected by either parameter.

The size of the diffuse neck resulting from electrical pulsing was found to be irrespective of the material pulsed, but dependent on the parameter set used for pulsing. Considering both aluminum alloys, every heat-treatment/parameter-set combination (excluding the 5052-“As Is” specimen) displayed a diffuse neck in their respective displacement profile. Parameter Set 2 consistently produced a greater diffuse neck throughout all combinations. This leads to the conclusion that with any aluminum alloy/heat-treatment combination, the greater pulsing frequency of Parameter Set 2 developed a larger diffuse neck compared to the greater magnitude of pulses in Parameter Set 1. As stated previously, the diffuse necks produced by electrical pulsing are minute compared to diffuse necks due to superplastic deformation [15, 16]. Another notable difference experienced with the electrically pulsed tests was where fracture occurred. On a majority of the non-pulsed baseline tests, ultimate fracture occurred at roughly one-third or two-thirds of the test region. The electrically pulsed tests consistently fractured near, or at, the center of the testing region.

FUTURE WORK

For this research, each of the materials was investigated using the same pulsed parameter sets. While this allows for a cross-comparison of the effectiveness of the globalized parameter set, increased performance would be expected for each material if individual optimized conditions were determined for each material. Before using this technique on any one of these materials, it is highly recommended that this optimization be performed.

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