VIABILITY OF ELECTRICALLY TREATING 6061 T6511 ALUMINUM FOR USE IN MANUFACTURING PROCESSES

Jarred C. Heigel, Joseph S. Andrawes, and John T. Roth
Mechanical Engineering
The Pennsylvania State University at Erie, The Behrend College
Erie, Pennsylvania

Mohammed E. Hoque, and Ralph M. Ford
Computer Engineering
The Pennsylvania State University at Erie, The Behrend College
Erie, Pennsylvania

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ABSTRACT

Electrical flow, applied before and during deformation, is shown to reduce the specific energy and flow stress of aged 6061 T6511 aluminum; it also creates apparent macroscopic strain-weakening in the material. When applied to annealed 6061 aluminum, the electricity not only further reduces the specific energy and flow stress but also delays the onset of necking; increasing the workability of the material. The precipitates and grains of the aluminum are investigated for alterations due to either annealing or electrical flow. Both treatments are shown to affect the size and number of the precipitates and decrease the grain size. However, the electricity has an effect on the mechanical properties beyond the changes in precipitates and grains; suggesting that electrical flow has the potential to reduce the forces generated in bulk deformation or material removal processes beyond the level that can be achieved by temperature alone.

INTRODUCTION

In order to lower manufacturing costs, it is vital to reduce the energy consumed during operations, increase tool and die life, and decrease equipment size and cost. For bulk deformation and material removal processes, all three of these cost contributing factors can be directly linked to the forces generated during production. Thus, if the generated forces can be reduced, the manufacturing costs will correspondingly decrease. For bulk deformation based processes, this is typically accomplished through the application of heat. By heating the workpiece, the material becomes more pliable and the forces necessary for deformation are reduced. Although increasing the workpiece temperature requires additional energy, in most cases, it has been found that the overall energy expended to produce the part is decreased. Furthermore, by decreasing the force, the size of the equipment required for the process is decreased and the tooling/die life is increased. Unfortunately, increasing the workpiece temperature has drawbacks. As the temperature is increased, the material becomes more reactive, adhesion between the workpiece and dies increases, and the effectiveness of lubricants decreases. Therefore, if an alternative means of decreasing the forces necessary to deform the workpiece can be devised, it has the potential to improve current bulk deformation processing techniques.

Material removal processes, on the other hand, already have significant adhesion problems due to localized heating caused by the cutting process. Therefore, in most cases, while increasing the workpiece temperature increases the material's pliability, it actually decreases the effectiveness of the cutting operation. Considering this, material removal processes can be improved if a means can be devised to decrease the cutting forces without increasing adhesion.

Given these problems inherent with increasing the workpiece temperature, it is desirable to devise an alternative means of increasing a material's pliability. To that end, a reduction in the energy under the material's stress-strain curve will typically reduce the force required to deform or cut the material. This can be demonstrated through the short representative listing of simplified equations for approximating the forces/pressures generated in various processes (Kalpakjian, 2003):

Forging: $$p_{avg} = \bar{Y}\left(1 + \frac{2\mu r}{3h}\right)$$

Flat Rolling: $$p_{avg.EntryZone} = \left(\bar{Y} - \sigma_b\right)\frac{h}{h_o}e^{\mu(H_o - H)}$$

$$p_{avg.ExitZone} = \left(\bar{Y} - \sigma_f\right)\frac{h}{h_f}e^{\mu H} \tag{1}$$

Extrusion: $$p_{avg} = \bar{Y}\left(1 + \frac{\tan\alpha}{\mu}\right)\left[R^{\mu^*\cot\alpha} - 1\right]$$

Drawing: $$p_{avg} = \bar{Y}\left(1 + \frac{\tan\alpha}{\mu}\right)\left[1 - \left(\frac{A_f}{A_o}\right)^{\mu^*\cot\alpha}\right]$$

As can be seen, in each of the cases, the generated forces/pressures are a function of three categorical areas: material properties, friction, and geometry. Similar relationships exist for most other deformation and material removal processes. Since the geometry of a given part is usually fixed, either the friction or the material properties need to be modified if the forces/pressures are to be reduced. For bulk deformation processes, the forces/pressures are controlled by the flow stress (true stress required to continue plastic deformation at a particular true strain). Similarly, for material removal processes, the forces are typically related to the specific energy (area under the stress-strain curve at a particular strain). Both of these parameters are directly influenced by the shape of the material's stress-strain curve. Therefore, if a material's response can be altered such that, at strains beyond yield, the corresponding flow stress and specific energy are reduced, the forces required for both deformation and cutting will be reduced.

Along these lines, several works have been published that discuss the effect of an electrical current on the diffusion characteristics, and consequently, the flow stress or specific energy of a metal. In 1969, it was reported by Troitskii that electric current pulses reduce the flow stress in metals. Subsequently, several other investigations have been conducted to investigate the effects that electricity has on various mechanical and material properties. Research by Xu et al. (1998) demonstrated that continuous current flow can enhance the recrystallization rate and grain size in select materials. Electrical flow has also been linked by Chen et al. (1998) to the formation and growth of inter-metallic compounds. In several works by Conrad (2000, 2000, 2002), very short duration, high density electric pulses have been shown to affect the plasticity and phase transformations of metals and ceramics. Conrad also demonstrated that the pulses affected the precipitation rate of the metal; either enhancing or retarding the rate.

With regards to aluminum, Conrad found that an electric field reduced the flow stress. Furthermore, when analyzing his own results, Conrad suggested that the application of either a continuous or short duration high density current during diffusion based processes may reduce the required temperature, energy, and overall cost of the process. From these studies, it appears that the energy associated with an electrical flow has the potential to reduce the forces produced during deformation and material removal processes without resulting in a significant rise in temperature.

PREVIOUS RESEARCH

In a previous study by the authors (Andrawes et al., 2004), tensile tests were performed which demonstrated the effects that electrical current has on a material's mechanical properties. Several tests of each treatment were performed to verify consistency (a representative curve of each treatment is presented: Fig. 1a - 1f). The results of the treatments with electrical current were also compared to the effect of annealing in this previous study. As a base line, in Figure 1a, the stress-strain behavior of the aluminum prior to any treatments is provided. Similarly, Figure 1b depicts the typical stress-strain behavior of the material after annealing. As can be seen, the annealing process lowers the yield point in addition to decreasing the ultimate strength and engineering toughness of the aged aluminum. These three properties are of particular importance when investigating the stress-strain behavior, due to the fact that they directly influence the forces generated during deformation or material removal processes.

In this previous study, it was also found that, when applying an electrical current during testing, the curve develops a uniquely different shape. More specifically, the maximum stress decreases and no longer occurs at the point of necking. Figure 1c presents the typical stress-strain behavior exhibited by the aged aluminum when a current of 1350 Amps was present in the material during deformation. As can be seen, the stress crests soon after yielding. In the previous study, however, it was proven that the material did not begin to neck until the bump in the curve that occurs just prior to failure. This phenomenon, which was evident in all of the tests conducted at this current level, presents a highly unique situation. On a macroscopic scale, the material's strength is decreasing as the strain increases. This virtual strain weakening drastically reduces the flow stress and specific energy of the aluminum. From this result, it is plausible that an electric current can be used to reduce deformation or machining forces within a workpiece.

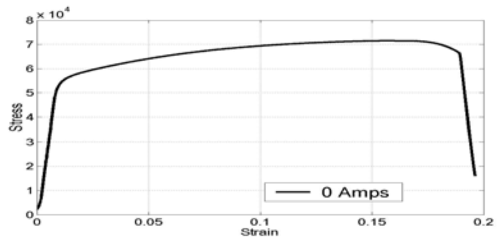

FIGURE 1a. 0 AMPS

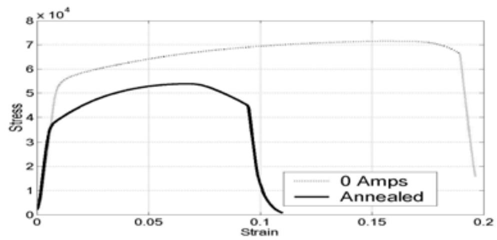

FIGURE 1b. ANNEALED

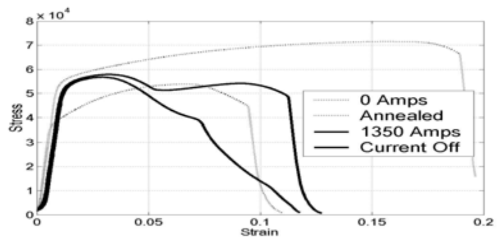

FIGURE 1c. 1350 AMPS & CURRENT OFF HALFWAY THROUGH

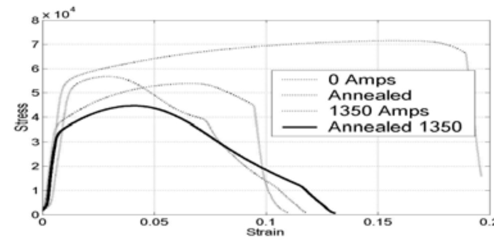

FIGURE 1d. ANNEALED WITH 1350 AMPS

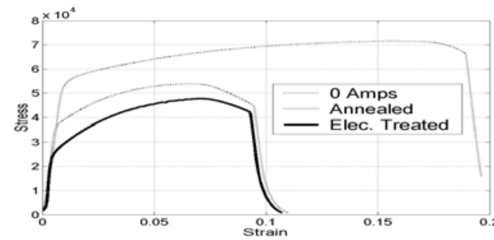

FIGURE 1e. ELECTRICALLY PRETREATED

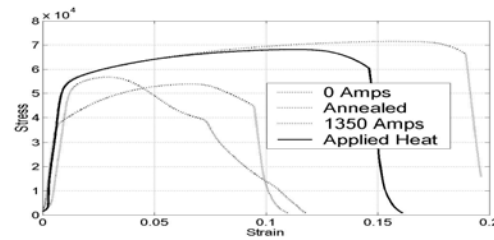

FIGURE 1f. APPLIED HEAT

In order to further examine the effect of the current on the macroscopic strain-weakening mechanism, tests were performed in which the current was removed in the middle of the run (also in Fig. 1c). As can be seen from the figure, when the current is removed, the normal strain hardening behavior resumes, acquiring a shape in the later part of the curve that resembles the curve from the annealed samples.

As a part of the earlier investigation, electric current was also applied to annealed specimens to determine if the current is able to further affect the aluminum. As can be seen in Figure 1d, applying the current to previously annealed specimens resulted in a further reduction of the material's specific energy. There is also a reduction in the maximum stress and flow stress when both treatments are used. However, this decrease is not as drastic as the decrease that exists when comparing the 0 Amp and 1350 Amp samples. It is interesting to note, however, that when applying current to the annealed specimens, the neck occurs about 50% later than the necks of either the annealed or 1350 Amp samples. This is interesting since, after annealing the aged 6061 T6511 aluminum, applying current brings the strain at necking closer to that of the original 0 Amp samples.

The effects of an electrical pretreatment were also investigated as a part of this previous study. The pretreatment process involved applying 1350 Amps to specimens until the temperature reached 500˚F. After pretreatment, the workpieces were allowed to air cool to room temperature. Upon deformation, it was discovered that the pretreatment results are very similar to the results found after annealing the samples (refer to Fig. 1e). An interesting aside to consider when comparing the pretreated and annealed curves is the difference in time and temperature. The pretreated specimens required approximately 30 seconds to treat and 5 minutes to cool, as opposed to the 8 hour processing time required for annealing. Furthermore, the pretreated specimens never reach annealing temperatures.

To verify that the observed effects of the electricity on the specimens were not attributable to the corresponding temperature rise, several tests were run in which a band heater increased the temperature of specimens during deformation. For the electrical tests, the specimens started at roughly room temperature and heated (due to the electrical resistance) to approximately 270°F. Considering this, a similar effect was created using a conventional non-contact band heater during testing. A typical curve for specimens using the band heater that reached approximately 270°F during the testing can be found in Figure 1f. While it can be seen that the material had a slight decrease in energy when compared to the untreated stock, the drastic shape change achieved with the applied current is not present. This shows that the applied current has a larger affect on the aluminum's properties than accounted for by the increase in temperature.

Considering the significant affect that electrical treatments had on the stress-strain behavior of the aged aluminum, the

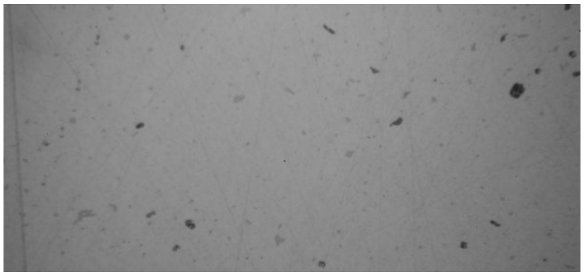
FIGURE 2a. PRECIPITATES: 0 AMP

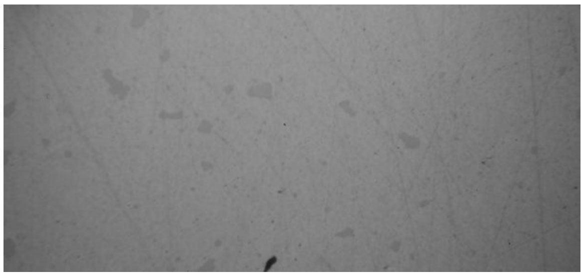
FIGURE 2b. PRECIPITATES: ANNEALED

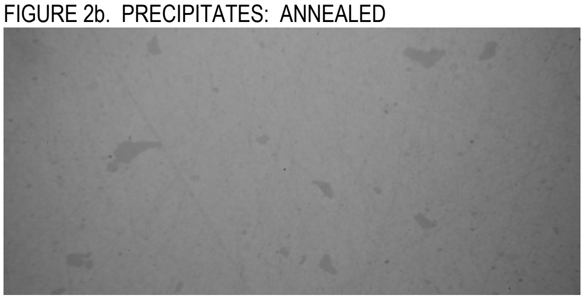
FIGURE 2c. PRECIPITATES: 1350 AMP

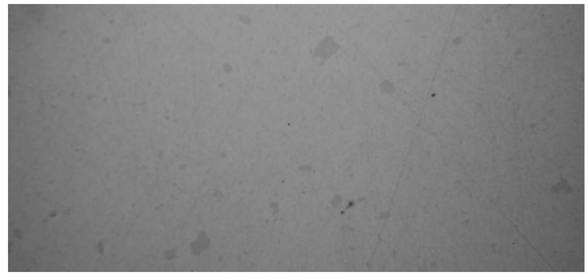
FIGURE 2d. PRECIPITATES: ANNEALED & 1350 AMP

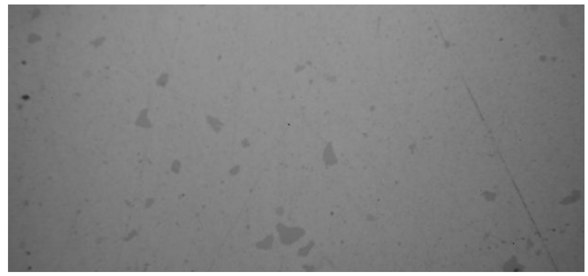
FIGURE 2e. PRECIPITATES: ELECTRIC PRETREATING

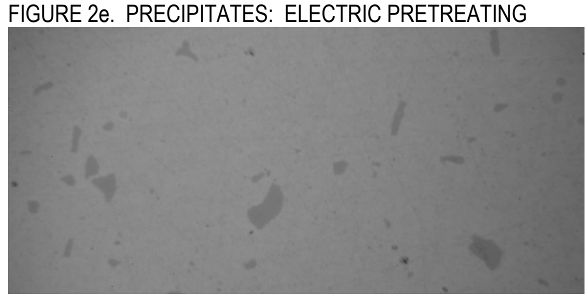
FIGURE 2f. PRECIPITATES: CONVENTIONALLY HEATED

current research, discussed herein, investigates any microstructural alterations caused by the electrical treatment. To accomplish this, both the precipitates and the grain boundaries of the aluminum were studied.

PRECIPITATE ANALYSIS

A precipitate analysis of the specimens from each type of treatment was conducted to help isolate which changes in the aluminum were due to microstructural alterations and which were a consequence of the flowing electricity. From Figure 1c, where the electricity was discontinued during deformation, it is apparent that both of these effects are present. Therefore, before electricity becomes a viable technique for reducing the forces associated with deformation and machining, it is important to isolate any microstructural changes occurring within the specimens so that these changes can be compensated for in subsequent processing.

When studying the precipitate characteristics of the aged 6061 T6511 aluminum, there are several parameters which are of importance. Provided below is a brief discussion of the precipitate and grains typically found in 6061 aluminum. For a more detailed discussion, refer to Aluminum: Properties and Physical Metallurgy (1984). The most significant precipitate in 6061 aluminum is Mg_2Si (the black shapes in the metallographic images above). Mg_2Si is known to strengthen aluminum, therefore, any changes in the amount, number, or size of this precipitate caused by the various treatments is highly noteworthy. The second precipitate in 6061 aluminum is composed of one of four compositions: Fe_3SiAl_{12}, $Fe_2Si_2Al_9$, Mn_3SiAl_{12}, or Cr_3SiAl_{12}, depending on the percent composition of the alloying materials. This irregularly shaped precipitate is grey in color and is not known to have an affect on the properties of the aluminum. However, the amount, number, and size of the precipitate is still important to monitor.

For the images presented herein, an aus JENA Neophot 21 metallograph was employed in conjunction with a high-resolution digital camera. The micrographs of each treatment, at the size presented within this paper, have a magnification of approximately 1175x. Representative pictures of each treatment can be found in Figures 2a through 2f. As the treatments were varied, minor fluctuations in precipitates were noted. However, current visual inspection techniques were inadequate for statistically determining the causal effects of the treatments. Therefore, a precipitate analysis software program was written that was capable of isolating grey and black shapes from the background in such a manner that the precipitate amount, size, and number could be statistically determined for the 6061 aluminum.

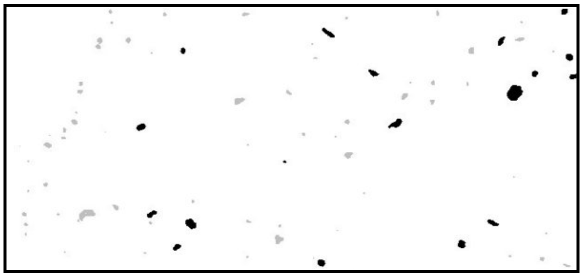

FIGURE 3a. REPRESENTATIVE 0 AMP FROM PROGRAM

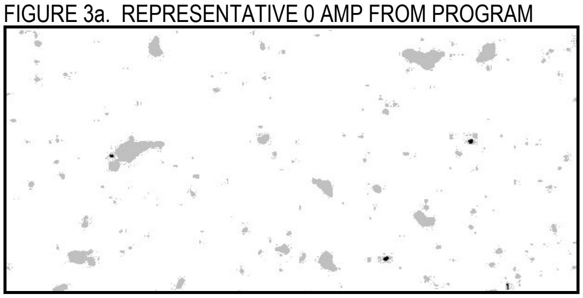

FIGURE 3b. REPRESENTATIVE 1350 AMP FROM PROGRAM

Precipitate Analysis Program

Using an adaptation of the blob analysis routines developed for machine vision applications, a software package was specifically designed and written for analyzing the precipitates within 6061 aluminum. By examining the pixels of the micrographs, the program is able to isolate the grey and black precipitates from the background and determine the amount, number, and size of each type of precipitate in the image. To accomplish this, the micrograph is first converted to grey scale. Once this is accomplished, a background correction is performed to eliminate the gradients in the micrograph that occur due to light concentrations from the metallograph's lenses (note that the upper center area of Figures 2a - 2f are brighter than the corners of each image). This background compensation is required in order to correct for the pixel intensity of the background so that the grey and black regions are not misidentified due to the gradient.

After correcting for background gradients, the program operates by applying a blob analysis routine to the image in order to isolate the precipitates. The sensitivity of the program can be adjusted to ensure that all precipitates are recognized. After isolating the shapes, intensities are assigned to each of the precipitates. At this point, the user is prompted to enter intensity ranges for the grey and black regions. Due to reflectivity differences between specimens, changes in surface angles, and miscellaneous other variations, the intensity of each specimen will vary slightly. Therefore, the range of pixel intensities from the grey and black precipitates will also fluctuate slightly. Thus, at this point, the analysis program is not fully automated. Instead the operator must judge appropriate ranges. To do this, the program displays a three color image to clearly distinguish the background, grey, and black regions (Fig. 3a & 3b). The user accepts the results or changes the intensity ranges until acceptable results are obtained. The resulting images and corresponding text file are then saved. The text file contains the user inputs and the program results. In order to statistically determine the alterations resulting from the various treatments, several images from each type of treatment were analyzed. The categorical results were subsequently averaged. The compilation of the effect of the various treatments on the amount, size, and number of black (Mg_2Si) and grey (Fe_3SiAl_{12}, $Fe_2Si_2Al_9$, Mn_3SiAl_{12}, or Cr_3SiAl_{12}) precipitates can be found in Table 1 & 2.

TABLE 1. PROGRAM RESULTS: BLACK PRECIPITATES

	0 Amps	Annealed	1350 Amps	Annealed and 1350 Amps	Electrically Pretreated	Applied Heat
# of Precipitates						
Total Precipitate Count	181	255	163	249	188	126
Black Precipitate Count	23	2	3	2	2	2
Total Precipitate Amount (Pixels)						
Total Precipitate Amount	3258	3825	4401	6225	5452	5796
Total Black Precipitate Amount	1357	58	45	13	56	46
Avg Precipitate Size (Pixels)						
Avg Precipitate Size	18	15	27	25	29	46
Avg Black Precipitate Size	59	29	15	6	28	23

Black Precipitate Analysis

When reviewing Table 1, several dramatic effects concerning the black precipitate are apparent. Most noticeable is that each treatment drastically reduces the amount of the black precipitate (by 96% - 99%). The number of regions where the precipitate appears is also severely reduced (by 87% - 91%), and the size is decreased (by 51% - 90%). This drastic decrease in every measure of the black precipitate can be correlated to the corresponding macroscopic decreases in strength and specific energy that occurred in the aluminum due to each type of treatment.

Comparing the program results from the annealed and the 1350 Amp treatments, it can be seen that both treatments cause roughly the same decrease (96% vs. 97%) in the total amount of black precipitate. Also, there is little difference between these two treatments in the decrease of the number of regions (87% vs. 91%). However, there is a significant difference in the effect of these two treatments when the size of the regions is considered; annealing produces a 51% decrease in the size, whereas an applied current of 1350 Amps results in a 75% decrease in the size of the black regions. These findings help to support the energy reductions seen in the stress-strain curves of the samples. Annealing produces a 64% decrease in energy under the curve, whereas an applied current of 1350 Amps produces a reduction of 66%. In all of the previous testing, the applied current consistently created a slightly larger energy reduction. This can be partially explained by the applied 1350 Amps creating smaller precipitate sizes than annealing can produce. The smaller Mg_2Si precipitates create less lattice strain,

TABLE 2. PROGRAM RESULTS: GREY PRECIPITATES

	0 Amps	Annealed	1350 Amps	Annealed and 1350 Amps	Electrically Pretreated	Applied Heat
# of Precipitates						
Total Precipitate Count	181	255	163	249	188	126
Grey Precipitate Count	158	252	159	247	185	122
Total Precipitate Amount (Pixels)						
Total Precipitate Amount	3258	3825	4401	6225	5452	5796
Total Grey Precipitate Amount	1896	3780	4293	6175	5550	5612
Avg Precipitate Size (Pixels)						
Avg Precipitate Size	18	15	27	25	29	46
Avg Grey Precipitate Size	12	15	27	25	30	46

consequently, the energy required to deform the material is reduced due to dislocations moving with less effort. Also of note, when the annealing and the 1350 Amp treatments are combined, even greater reductions occur in the black precipitates. The combined treatments produce a 99% decrease in the total amount of black precipitate. The number of regions remained constant; however, the size of the regions decreased by 90%. These changes correspond to a reduction in energy under the stress-strain curve of 71%. This energy reduction also agrees with the combined treatment having smaller black regions than the 1350 Amp applied current, which only saw a 66% decrease in energy.

Of particular interest, the precipitate analysis shows that an electrical pretreatment produces nearly identical reductions in amount, number, and size of black precipitate in comparison to annealing treatments. It is interesting to note, however, that the energy under the stress-strain curve of the pretreated sample only saw a reduction of 44%, whereas the annealed sample saw an energy reduction of 64%. Therefore, there must be another parameter that affects the strength of the material to explain the difference in energy reduction.

Finally, when the samples are conventionally heated during testing from room temperature to 271˚F, the total amount of black precipitate in the final material is decreased by 97%, the number of black regions is decreased by 91%, and the average size is decreased by 61%. These values lie between the values for the annealed and applied 1350 Amp treatments. Since 271˚F is well below the recrystallization temperature required for annealing, it suggests that the application of heat during deformation has a more drastic effect on the decrease in the Mg_2Si precipitate than occurs during the much longer annealing process. However, when considering the energy under the stress-strain curve, the reverse is true (heating during deformation results in a 29% decrease). This observation possibly indicates that the Mg_2Si precipitate is not the only strengthening mechanism in the aluminum. Moreover, when comparing the 1350 Amp and conventional heating results, it also becomes apparent that electrical flow has an effect on the material properties beyond that accounted for by the change in the Mg_2Si precipitate.

Grey Precipitate Analysis

Even though the grey regions do not effect the strength of the aluminum, it is important to monitor the changes caused by each treatment. The grey regions, unlike the black regions, do not show a uniform change in their number; treatments may increase or decrease the number of grey regions. There is, however, a uniform increase in the amount and size of the precipitates (refer to Table 2).

When comparing the annealed samples and the 1350 Amp samples, there is a vast difference in the amount of increase in the grey regions (60% vs 0% respectively). In addition, there is also a difference found in the increase in the total amount of grey precipitate (99% vs 126%). However, the largest difference can be found in the size of the grey regions; the annealed samples saw an increase in size of 25%, whereas, the 1350 Amp samples saw an increase of 125%. When applying a current of 1350 Amps to the specimens after annealing, the number of grey regions sees a slight increase in comparison to samples that were only annealed (56% vs 60%). When comparing the amount of the grey precipitates, however, the difference is much more significant: 226% for annealed & 1350 Amp vs. 99% for annealing alone. Another large difference exists with respect to the size of the regions. When applying current to annealed specimens, an increase in size of 108% occurs , whereas, annealing alone only creates an increase of 25%. These findings suggest that the annealing and applying current have an additive effect with respect to the grey precipitate.

Comparing the effects of an electrical pretreatment with the effects of annealing, it can be seen that there is a significant difference in the number of grey regions (17% vs 60%), the amount of grey precipitate (193% vs 99%), and the size of the regions (150% vs 25%). Therefore, pretreating with electricity has a different affect on the grey precipitates than the annealing.

The conventionally heated specimens were the most dissimilar of all of the treatments. It should be noted that the conventionally heated specimens are the only case where the number of the grey precipitates actually decreased. However, the treatment also resulted in the largest increase in size; overall providing a comparable increase in the amount of grey precipitate as that found in the other treatments.

GRAIN BOUNDARY ANALYSIS

As previously stated, before electricity becomes a viable technique for reducing the forces associated with deformation and machining, it is important to isolate any permanent alterations occurring within the specimen so that these changes can be compensated for in subsequent processing. Therefore, it is important to not only examine changes that

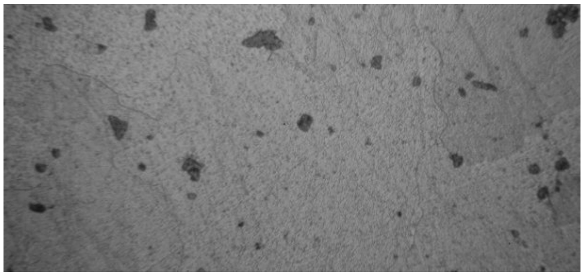
FIGURE 4a. GRAIN BOUNDARIES: 0 AMP

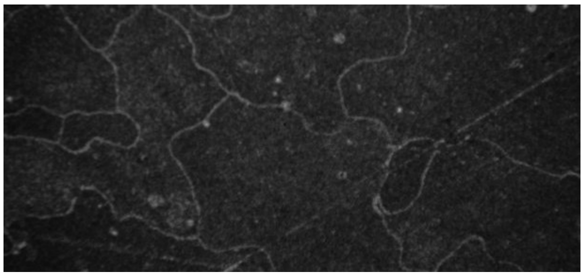
FIGURE 4b. GRAIN BOUNDARIES: ANNEALED

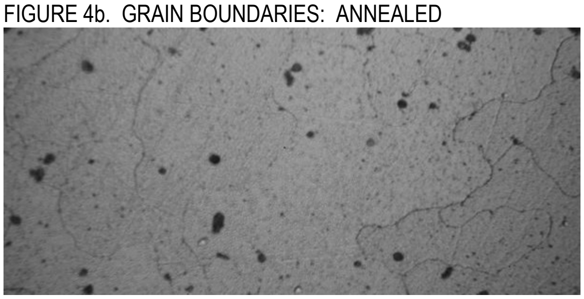
FIGURE 4c. GRAIN BOUNDARIES: 1350 AMP

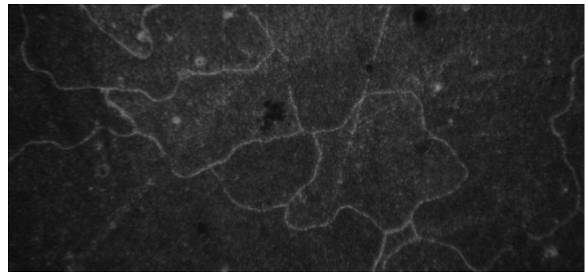
FIGURE 4d. GRAIN BOUNDARIES: ANNEALED & 1350 AMP

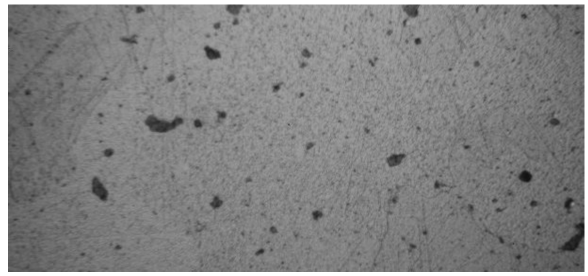
FIGURE 4e. GRAIN BOUNDARIES: ELECTRIC PRETREATING

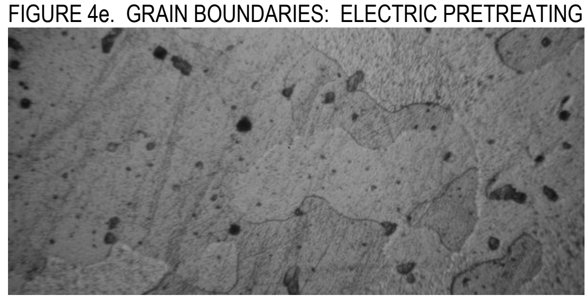
FIGURE 4f. GRAIN BOUNDARIES: CONVENTIONALLY HEATED

occurred in the precipitates within the aluminum, but also to examine any other changes in the aluminum. Of particular interest is any changes that the treatments had on the aged 6061 T6511 aluminum grains. Only after accounting for the changes in both the grains and precipitates can the affect of the electrical flow on the material's mechanical properties be identified. In order to examine the aluminum grain structure, samples were etched with Keller's reagent. For additional information on either Keller's reagent or the etching procedure refer to texts or standards describing aluminum polishing techniques. One important point worth noting with the etching process, however, is that the etchant appears to have reacted with the grey regions, giving them the same color as the black regions. Because of this, the etched pictures can only be used to compare the grain boundaries.

As was true with both the stress-strain and precipitate comparisons, a baseline must first be established. In each of these cases, the baseline used was the aluminum specimens with 0 Amps applied. From Figure 4a, it can be seen that, even after the sample is etched, the grain boundaries are difficult to see. However, when comparing the 0 Amp's grain size to those for the other treatments (Fig. 4b - 4f), it is apparent that the 0 Amp specimens have larger grain sizes than those found with any of the treated samples other than the electrically pretreated sample. While it is important to note that both the annealing treatments and treatments involving electrical flow result in a finer grained material, the change in grain size is not significant enough to have a significant effect on the stress-strain behavior of the aluminum. When comparing the various treatments, it is also clearly apparent that, when etched, the annealed samples develop a nearly opposite appearance as found with the non-annealed samples (Fig. 4 b & d versus a, c, e & f). As can be seen in Figures 4b and d, the change caused by annealing the aluminum exists in both the specimens deformed without electrical current and also the annealed specimens deformed while electrical current was applied. For both of these annealed cases, the grain boundaries are white in appearance and the precipitates appear white as well.

This difference is of particular interest since it implies that annealing causes a permanent change to the aluminum. Furthermore, as can be seen in Fig 4c, when electricity is applied without annealing, a similar change does not occur. Therefore, while electrical pretreatments produce similar stress-strain relationships as those found when annealing, the pretreatment does not cause severe permanent changes to the aluminum. In addition, electrical pretreatments are completed in less time, do not elevate the workpiece above the recrystallization temperature, and do not alter grain size. Although the electrical pretreatment creates resistive heating, the temperatures remain below recrystallization. By maintaining a lower temperature than is typically created during resistive heat treatments, the electrical flow, rather than the temperature, provides the motive force for changing the material and thereby does not cause the permanent reactive change in the aluminum that traditional annealing or resistive heat treatments cause. Thus, the electrical pretreatments may provide an attractive alternative to annealing.

CONCLUSIONS

By correlating the stress-strain behavior of the aluminum to the corresponding precipitate and grain analysis, the changes in the mechanical properties due to both annealing and electrical pretreating are fully addressed. However, the precipitate and grain alterations do not sufficiently account for the reductions in both the specific energy and flow stress that occur when applying an electrical current while deforming the material. This suggests that the current passing through the workpiece has an affect on the material flow that is not accounted for by the physical precipitate or grain alterations. Thus, it appears that an electrical current can be applied to aluminum-based deformation and material removal processes to reduce the forces and energy required to produce a part; an issue currently being investigated. The findings also show that the affects of strain hardening are reduced or eliminated if the electricity is applied during deformation.

When analyzing the precipitates, several changes occur during the application of the electricity that are significant. When the electricity is applied during deformation, the amount, number, and size of both the Mg_2Si and the Fe_3SiAl_{12}, $Fe_2Si_2Al_9$, Mn_3SiAl_{12}, or Cr_3SiAl_{12} precipitates in the aluminum are affected. This is also true when annealing or electrically pretreating the aluminum.

In addition, applying electricity during deformation results in a greater reduction in the energy required to deform the material than can be achieved through annealing. Furthermore, it is shown that, when applying electricity to an annealed material, even larger reductions in energy are possible. Moreover, it was shown that necking occurred at higher levels of strain in the specimens that were both annealed and deformed while electricity was applied than occurred in the specimens that were only annealed. Therefore, the specific energy is reduced and the working range of the material is increased when electricity is applied to a material which has been previously annealed.

When analyzing the grains of the aluminum, a significant difference was found between the electrical effects and the annealing effects when etched. Comparing the annealed and non-annealed specimens, annealing caused the etchant to reacted with the aluminum. This permanent change to the aluminum, however, did not occur when the material was deformed under an applied electric current or when electrically pretreating the material.

Along those lines, as a part of this study, a comparison was completed between the viability of using electrical pretreatments of the aluminum rather than annealing to reduce the forces created during deformation or material removal processes. It is worth noting, that electrical pretreatments differ from resistive heat treating with regards to temperature, duration, and transport mechanism. When comparing the electrical pretreatments to annealing, it was found that the pretreatments resulted in a greater reduction in energy under the stress-strain curve, created a larger reduction in Mg_2Si precipitate amount, required less time, did not affect the grain size, and did not cause the permanent change to the aluminum that the annealing caused. Given these advantages, the use of electrical pretreatments as alternatives to annealing is currently being investigated.

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