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Materials Today: Proceedings XX (2016) XXX–XXX

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PMME 2016

Yield identification by passing an electric current ☆

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Abstract

Material characterization is the backbone for structural components and for manufacturing. The material characterization provides elasticity, yielding, tensile strength, necking, and total elongation. These material properties provides the limits for operations on the components either in performance or in manufacturing. Among these properties yielding is the one which separates the members in elastic deformation than in plastic deformation. Thus identification of yielding is important to accurately design the components. Traditionally the material was characterize through a tensile test and the deviation from elastic to plastic was considered as yielding. Due to continuous profile of tensile curve the yielding was identified by using 0.2% of offset strain. For elevated temperature the material was enclosed in the furnace with the desired constant temperature and further pulled using tensile test to characterize the material. In this paper an aluminium alloy is pulled through tensile test while passing the electric current. This current was set such a way that the specimen will get resistive heating providing the same temperature as in thermal furnace based heating. The tensile curves were then compared from baseline, thermal based heating and using electric heating. It was found that at yielding of the material, the temperature of the specimen was varied and provided the similarities such as yielding in case of electric current.

Selection and Peer-review under responsibility of International Conference on Processing of Materials, Minerals and Energy (July 29th – 30th) 2016, Ongole, Andhra Pradesh, India.

Keywords: Yielding, electric current, resistive heating, thermal heating, material properties

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1. Introduction

In manufacturing, understanding of material properties are crucial to produce a defect free product. To use the material till its limit is one of the utmost demand from the manufacturing industry without compromising the quality and performance. This is due to the demand from vehicle industry to produce strong and lightweight sheet metal parts. This demand raised because these industries are in constant pressure to meet the tighter environmental regulation. As mentioned the material should be used till its limits to produce the lighter parts, this paper discusses on identification of yield during warm or hot forming due to resistive heating by passing an electric current.

Devaluing the product due to its aesthetical look, industry is greatly interested in removing such effect from the metal final product. With the development of Electrically Assisted Manufacturing (EAM), researchers have determined that the mechanical properties of metallic materials can be significantly influenced by passing direct current through them [1-8]. Machlin et al. [9] was the first to observe such effects in 1959. Passing electric current through group 1A salts significantly affected ductility, flow stress, and yield. Later, in 1969, Troitskii [10] pulsed the electric current resulting in lower flow stress. By applying continuous electric current, Xu et al. [11] determined that certain material's recrystallization rates and grain sizes increased. Later, in 2007, Andrawes et al. [1] studied the effects of DC current on 6061aluminum alloy, where it was demonstrated that the stress-strain behaviour could be significantly altered. Heigel et al. [12] reported that the significant effect that electricity had on aluminium's stress-strain behaviour could not be attributed to the microstructural changes that were observed. Resistive heating due to electric current was investigated by Perkins et al. [13] which reported that the electrical effects were greater than what could be explained through resistive heating alone. Reduction in flow stress with the application of continuous electric current during plastic tensile deformation was determined by Ross et al. [14]. This work also demonstrated that the maximum achievable elongation was reduced with continuously applied current during tensile deformation. Another study by Ross et al. [15-16] examined the effects of electricity on a variety of different materials while undergoing tensile deformation. This study found that the electrical effects were largely independent of the microstructure, resistivity, or strength. Further it was also found that undesirable change in microstructure occurs by passing electric current which changes the mechanical properties according to the grain size [17]. On other hand it was noted that the flow stress during electric assisted forming is based on its thermal-mechanical behaviour [18-19]. Some investigations are also focused on improving the process capabilities by applying electric current such as reducing the forming forces [20] and reducing springback to produce the correct geometry [21-22]. In this paper, aluminum alloy 5083 was consider to study the material properties through different way of heating and deforming the material. The specimen was tested in tension by pulling the material in as-received condition, thermal heating and resistive heating by passing an electric current. The difference in material properties found through theses tensing are explained and discussed.

2. Experiment Procedure

Uniaxial tension tests were completed with a Tinius Olsen Universal Testing Machine. To control and continually record testing parameters such as strain and crosshead position, Tinius Olsen Navigator software was utilized. The dogbone specimens were elongated at a constant platen rate of 5.0 mm/min (0.196 in/min) until fracture for all tests.

2.1. Tensile specimen

To reduce the effects of material variability all tensile samples originated from the same sheet stock. The samples were prepared into strips from the sheet stock in 0^o to rolling direction; 45^o to rolling direction and 90^o to rolling direction. The strips were then machined (milled) into dogbone shaped samples with a gauge length of 73.66 mm (2.9 in) and a gauge width of 9.55 mm (0.375 in), which can be seen in Figure 1. A tolerance of ±0.015 in was utilized in the machining process to reduce the variability of the cross-sectional area, therefore reducing current density variability. Three samples were tested at each condition to analyse the repeatability.

2.2. EAM technique

For tests investigating the effects of passing electrical current through the sample a Lincoln Electric Idealarc-R3S welder was used to supply the DC current. The magnitude of the current passing through the sample was controlled by an air-cooled variable resistor allowing for constant magnitude over time. An Omega HHM592D Digital Clamp-on Ammeter monitored the current flowing from the welder. Haysite Reinforced Polyester and PVC tubing electrically insulated the fixtures from the testing equipment, ensuring that current flowed only through the specimen. The experimental set-up is shown in Figure 2. Current density is the parameter utilized in EAM research to quantify the amount of DC electric current flowing through the sample's cross section and has the units A/mm^2 (Amperes per millimeter square). For each test a constant DC current was held to achieve the desired current density; however, the current density increases slightly during deformation due to the reduction in the cross sectional area of the samples.

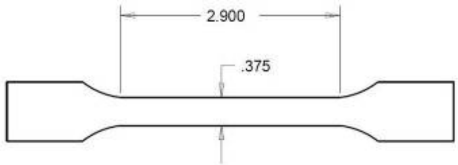

Fig. 1. Specimen Dimensions [23-24]

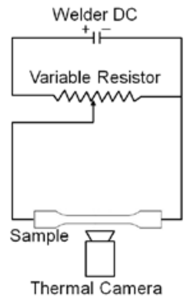

Fig. 2. Welder circuit setup for experiments [23-24]

2.3. Thermal technique

As DC current was applied to the samples in the previous section, heat generation occurred. To better understand the reduction/elimination of the PLC bands and if the behaviour modification is purely due to the thermal effects, a second set of tests were run. These tests were conducted at elevated temperatures produced by band heaters, without electrical current passing through the samples. The band heater covered the sample longitudinally leaving small gap to monitor temperature for thermal camera. The band heating system allowed for controlled and stable temperature conditions throughout each test. The same fixtures that were used in the electrical current tests were also utilized during the thermal investigation to reduce test variability. The samples were heated to the specified temperature prior to deformation (to make sure whole sample is at same specified temperature) and kept constant during the course of deformation. The band heaters continued to provide thermal energy throughout each test until fracture. The three temperature conditions were established to closely replicate the temperatures generated in the three electrical conditions.

2.4. Thermal data acquisition

To monitor and record the maximum temperature attained by passing an electric current through the sample without deformation and making sure to maintain that measured temperature in thermally activated environment (by band heaters) a FLIR ThermoVision A20m infrared thermal imaging camera was utilized. The camera captured data at 1 second intervals throughout the entirety of each tests using fifteen defined data points along the centerline of the dogbone specimen [23-24]. The camera captured the temperature data at each frame reflects the maximum and minimum value on the screen. This temperature was recorded and replicated through band heaters to investigate sole thermal effects.

The surface of the specimens that faced the thermal camera were painted black using high temperature paint to stabilize the emissivity of the sample, allowing for accurate temperature data.

3. Results and discussion

3.1. Tensile curve

Figure 3 provides the engineering stress strain curve for baseline, with continuous temperature of 180° C and with equivalent heat generation current density of 13.5A/mm². It can be noted that the tensile stress dropped in both cases as compared to baseline. It can also be noticed that the luders band can be found in baseline however they are eliminated by heating the sample. The elongation in both cases of heating is found similar. It is also noted that the elasticity lower in sample tested with electricity as compared to thermally tested sample.

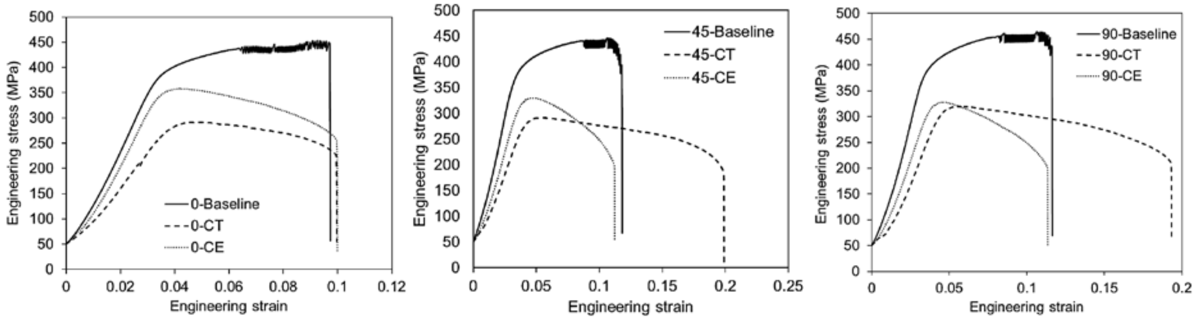

Fig. 3. Engineering stress-strain curve in 0 (left), 45 (center) and 90°(right) to rolling direction (CT – Continuous Temperature; and CE – Continuous Electricity)

Similar observation are found in 45° and 90° sample with the testing. However in both 45° and 90° orientation, the metal got longer elongation with continuous temperature as compared to the baseline. It was also noted that the sample failed earlier by passing current as compared to baseline. However in both cases the elasticity decreased in electrically treated sample as compared to the ones with thermally treated.

3.2. Thermal data analysis

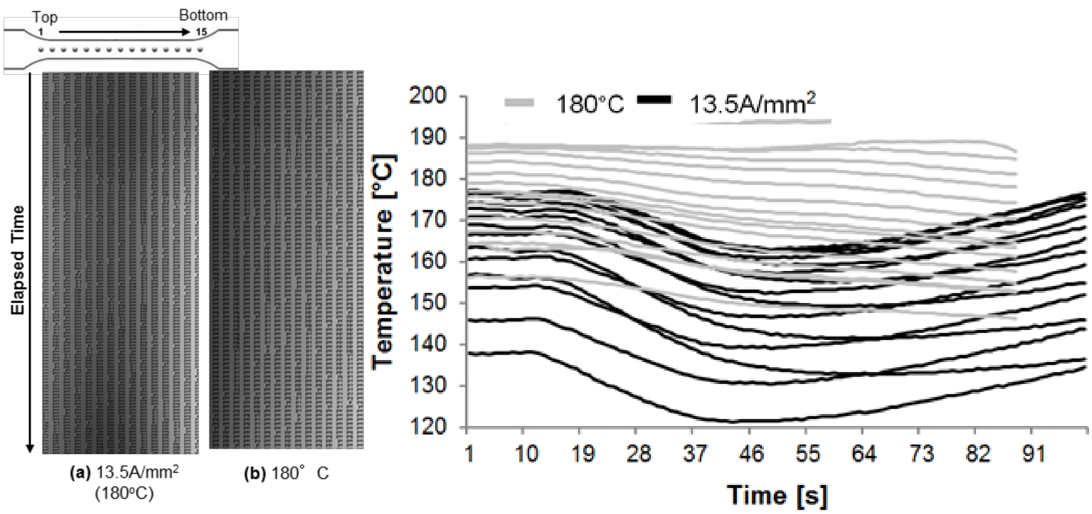

Fig. 4. Left: Temperature pattern on samples throughout deformation: 13.5A/mm², 180° C (black shade is hotter region) [24] and Right: Differences in thermal behavior between thermal and electrical conditions (0° to roll direction) [24]

As stated earlier the temperature conditions stated are approximate. This value is based on the reading captured from the thermal camera and exporting on screen with maximum and minimum temperature. These maximum and minimum temperatures are the saturated temperature after the electric current passed and waited for 2 minutes before the stretching started. Figure 4, 5, and 6 shows the temperature variation along the length of the sample and with respect to time. Each column of data is representative of a single data acquisition point and each row is a snapshot in time, elapsing until fracture. The darker regions represent higher temperatures.

During electrical tests, current flowed through the sample prior to deformation and a steady state temperature was reached. Once this temperature was achieved, the deformation would begin without modifying the current in any way. Figure 4a shows thermal data obtained from the 13.5A/mm^2 electrical condition which generates 180^o C in the sample by resistive heating. Initially the temperature was highest near the bottom of the sample (points 7-12). This temperature would then decrease as elongation progressed, subsequently followed by an increase sometime after the onset of plastic deformation. The elevated temperature zone migrated to the middle data points (7-9) before fracture.

The thermal condition of approximately 180^o C is represented in Figure 4b. It can be seen that the temperature was greatest at the beginning of the test, with the elevated temperature region at the top of the sample. As deformation progressed the temperature slightly decreased, although it was not significant.

Figure 4 (right) displays the temperature data contained in a graphical format to enable the reader to easily identify the temperature changes throughout the deformation. There are fifteen lines which correspond to the thermal camera acquisition points. As described earlier, both conditions decrease in temperature in the early stages of the deformation. The thermal condition temperature decreases steadily and does not increase in the way that the electric condition does.

Figure 5 captures each data point during thermal deformation, and plots them as temperature versus time for 45^o to roll direction sample. Initially, it was assumed that the thermal temperature, under the EAM method, would reflect the same test as of 0^o to roll direction sample data. However, in the figure shown below, the median temperature is approximately 150^o C, which is 30^o C below the expected. The temperature flow in the EAM method does mirror the 0^o to roll direction sample results, which is one similarity. Also, in the thermal deformation method, temperature remained around 180^o C, which was desired.

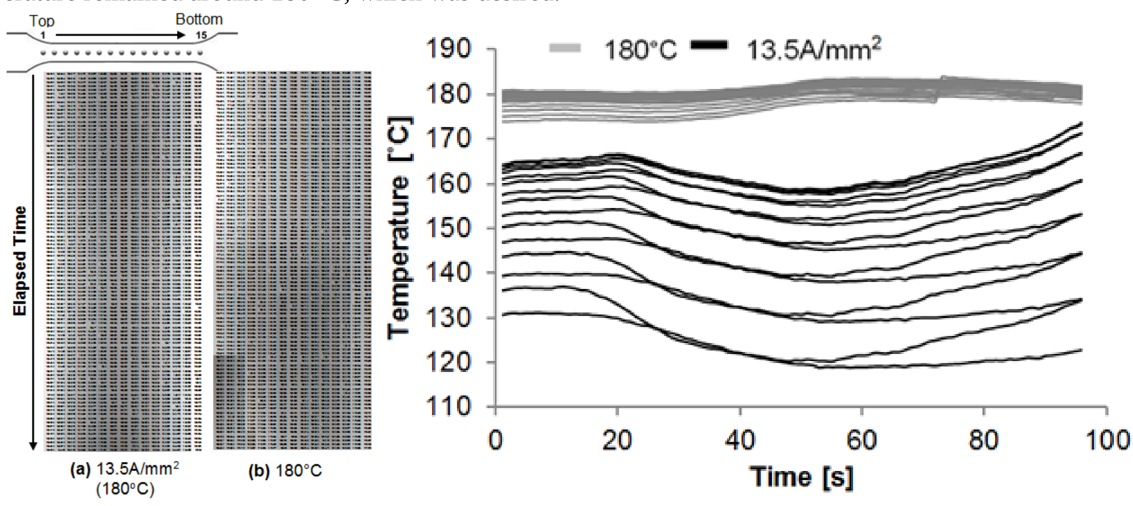

Fig. 5. Left: Temperature pattern on samples throughout deformation: 13.5A/mm2, 180°C and Right: Differences in thermal behavior between thermal and electrical conditions (45^o to roll direction)

In Figure 5b, temperature remained relatively constant during deformation, due to the constant temperature band heater applied during the test. In Figure 5a, temperature decreased initially and increased towards the end of the test. It appears, however, that the largest temperature fluctuations occurred on the edge regions of the test sample, which differs from the 0^o to roll direction test.

Figure 5 (right) represents the temperature distribution over time with reference to the temperature progression in Figure 5 (left). Unlike Figure 4, the temperature distributions overlap some, with some temperatures in the EAM method reaching 180° C. However the average temperature seen during the EAM process is less than the 180° C prediction from before. Instead, the average temperature is around 145° C.

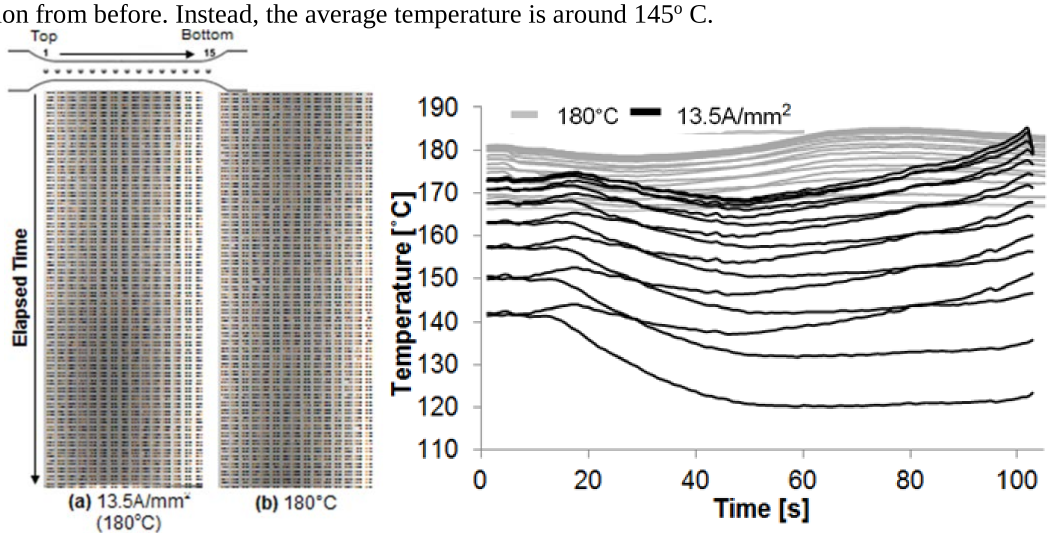

Fig. 6. Left: Temperature of samples throughout deformation: 13.5A/mm2, 180°C and Right: Differences in thermal behavior between thermal and electrical conditions (90° to roll direction)

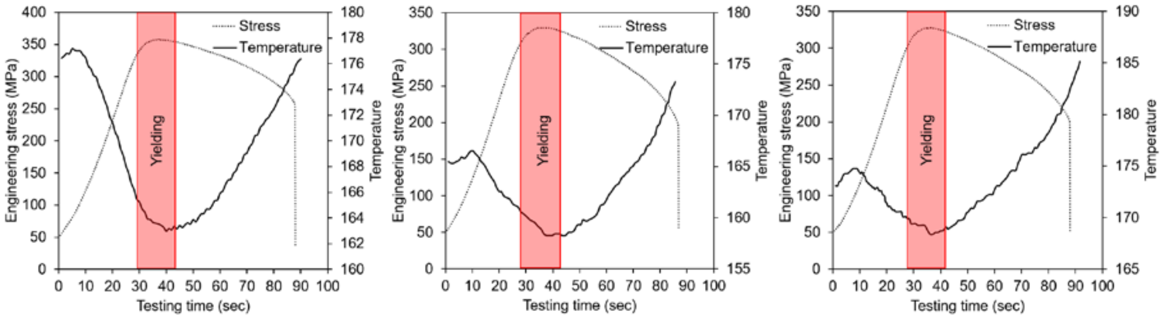

Fig. 7. Yielding identification from stress and temperature data by passing electric current through 0 (left), 45 (center), 90°(right) rolling direction samples

Figure 6 shows the temperature progression in 90° to roll direction sample through the same test criteria as with 0° and 45° to roll direction tests. Figure 6 (right) corresponds with Figure 6 (left), which notes the temperature distribution over time. The 180˚C remained constant over time, as was expected since temperature remained a constant input (Figure 6). The EAM method varied with temperature, due to the elongation causing a change in temperature.

Figure 7 provides the stress and temperature generated during tensile test using electric current through the specimen. It can be noticed that as the stress vary with respect to time of test, the temperature of a point also vary. At the start of pull the temperature of the specimen starts decreasing and then saturates to a point where the material starts yielding as see in stress curve. After yielding the temperature starts increasing. It seems that when the material is getting stretched before yielding the surface area of a specimen starts increasing and thus the temperature of the specimen starts decreasing. As soon as the material starts yielding i.e., breaking bonds between atoms the heat will suddenly dissipate to the surface and thus the point of increase in temperature. The another reason which would keep on adding the heat is that after yielding the material gets thinner and length increases. Due to reduction in area for the same current the current density increases which increases the heat generation. This observation can be seen in all direction of the material.

4. Conclusion

This paper relates to the identification of yielding during mechanical pull test by using an electric current. For this purpose an aluminium alloy 5083 was used to understand the behaviour. Tensile test were performed for as-received material, using thermal heating and using resistive heating of a specimen by passing an electric current. It was observed that the as-received material exhibits luders band. This luders bands were eliminated by using thermal heating as well as resistive heating. It was also observed that due to heating the elastic value decrease which was obvious as noted in literature. However for the same setting which could provide the similar temperature the specimen with electric current shows lower elastic value as compared to thermal heated specimen. From thermal analysis it was noted that the temperature of the specimen was constant because the whole surrounding was brought to a set temperature in thermal heating. However in resistive heating by passing electric current each individual point of specimen shows the drop in temperature at the stage when the material shows yielding and then increase due to reduction in area. This temperature valley point relates to the deviation of tensile curve after elasticity and can be consider as yield. Thus it can be concluded using thermal analysis the yield of a material can be identified by passing an electric current. This process would be very useful to identify the properties during warm and hot forming.

Acknowledgements

The authors would like to acknowledge the assistance of Glenn Craig for the fabrication of machine fixtures and the creation of the test samples and Penn State Behrend for providing the undergraduate research funds.

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