Effect of Current Carrying Length in Electric Pulse Aided Deformation

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1 Introduction

Electric Pulse Aided Deformation (EPAD) is gaining attention of researchers in recent years because of its ability to process high strength materials at relatively lower temperatures compared to hot working processes. Application of electric pulses during plastic deformation of a metal results in reduction of flow stress. This reduction can be due to both thermal and athermal effects. Increase in the mobility of dislocations during plastic deformation due to electron wind [1] is known as electroplastic (EP) effect [1, 2]. Note that the first paragraph of a section or subsection is not indented. The first paragraph that follows a table, figure, equation etc. does not have an indent, either.

Liu et al. [3] investigated the effect of pulsed DC current on the mechanical behaviour of TRIP 780/800 steel. Results showed that, there is a maximum instantaneous stress reduction of 285 MPa with temperature rise of 61 °C, whereas high temperature tensile tests at 115 °C showed that there is a flow stress reduction of 180 Mpa indicating the existence of EP effect. Roh et al. [4] studied the effect of

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X. Lei and V. V. Koryanov (eds.), *Proceedings of 5th International Conference on Mechanical, System and Control Engineering*, Lecture Notes in Mechanical Engineering, https://doi.org/10.1007/978-981-16-9632-9_24

applying multiple electric pulses on uniaxial tensile behaviour of Aluminium 5052-H32 alloy and concluded that electric pulses with same energy density but with different current densities caused identical stress strain behaviour (both instantaneous and permanent stress drops are same). Zhao et al. [5] studied the uniaxial tensile behaviour of Aluminium alloy AA5754 subjected to multiple electric pulses and reported that for a given energy density, the instantaneous stress drop increases with increase in the current density which indicates that current density has an independent effect on stress drop with same temperature rise.

Xie et al. [6] studied the effect of application of high frequency electric pulses on uniaxial tensile behaviour of dual phase steel DP 980. It was reported that only at 100 °C, electric current causes higher flow stress reduction compared to elevated temperature and for all other temperatures (up to 600 °C) flow stress increased due to passage of current. Magargee et al. [7] studied the electrically assisted tensile behaviour of CP titanium with and without forced air cooling conditions. They reported that flow stress reduction which was observed without forced air cooling (maximum temperature = 435 °C) is absent when forced air cooling (maximum temperature = 40 °C) was used.

From the literature, it is evident that stress reduction in EPAD is directly related to amount of joule heating [7], which in turn depends upon the current carrying length in the deformation zone. There is a need to reduce the overall joule heating in electric pulse aided tests as it is detrimental to material properties. The role of current density on instantaneous stress drop also requires further investigation as Roh et al. [4] reported that current density does not have an independent effect on stress drop but Zhao et al. [5] reported the contrary. In the present work, the effect of current carrying length on uniaxial tensile behaviour is investigated by performing single as well as multiple pulse experiments on modified tensile specimens. The role of current density on instantaneous stress drop with same temperature rise is also evaluated by conducting experiments with same energy density. Finally, the effect of applying different frequencies of electropulsing with same duty cycle on uniaxial tensile behaviour is studied.

2 Experimental Procedure and Methodology

Electrically assisted uniaxial tensile (EAT) tests are carried out on a universal tensile testing machine with a nominal strain rate of 10^{-3} s^{-1}. Material used in the experiments is a low carbon steel (C-Mn-440) in the form of a sheet with thickness of 1.02 mm. Figure 1a shows the dimensions of the standard specimen. Electric current is applied to the specimen through extensions provided in it as shown in Fig. 1b. Temperature rise in the specimen due to resistive heating is measured using single spot infrared pyrometer, which is focussed at the centre of the gauge length. A modified tensile specimen is designed with extensions to pass the electric current as shown in Fig. 1b. In the modified tensile specimen current carrying length (d) can be varied as shown in Fig. 1b. Three different current carrying lengths (d = 30 mm, 45 mm

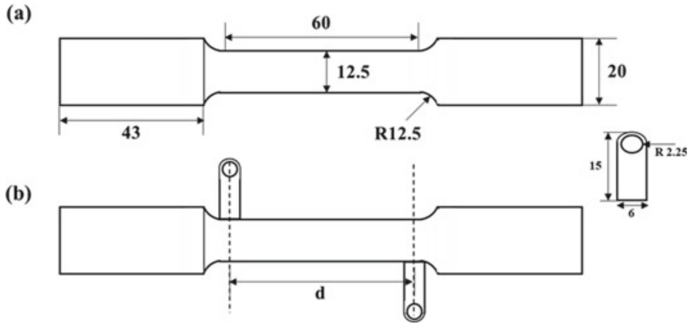


Fig. 1 Tensile specimens used in this work, **a** standard specimen, **b** modified specimen with current carrying length (d) as a variable

and 60 mm) are used in the present work. After confirming that modified specimens have same stress strain behaviour as that of the standard specimen, electric pulse aided experiments are performed.

To understand the independent effect of current density on instantaneous stress drop, three different current densities (J_0) (35.3, 27.3, 19.3 A/mm^2) and pulse durations (t_d) (2, 3.3, 6.7 s) with same energy density are used in the experiments. Current carrying length of 60 mm is kept constant in above experiments. Multiple pulse experiments are conducted at two different frequencies (f) (0.05, 0.1 Hz) with constant duty cycle (5%). Current density of 35.3 A/mm^2 is used in the above experiments.

3 Results and Discussion

The effect of added extensions to the standard specimen on tensile behaviour is studied by experiments. It is observed that, added extensions do not affect the original tensile behaviour. However, it is observed from experiments that decrease in the distance between extensions less than 30 mm has caused a shift in the failure location from centre of specimen to near fillet region. Hence, further reduction is not considered.

3.1 Effect of Current Carrying Length

Temperature of the specimen has increased instantaneously as soon as electric pulse is applied but the reduction in temperature is gradual. Maximum temperature reached is 190 ± 5 °C (measured at the centre of the gauge length) and it remains nearly same for all other current carrying lengths. Note that, overall joule heating is more for specimen with higher current carrying length. The effect of current carrying

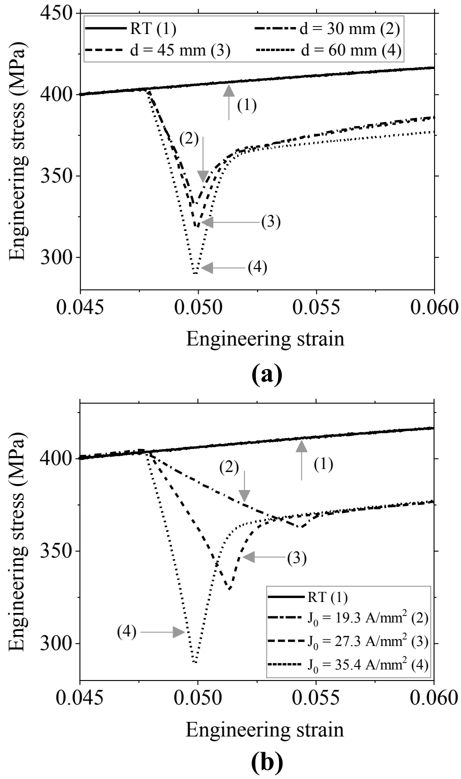


Fig. 2 **a** Effect of current carrying length and, **b** effect of current density on tensile behaviour

length on uniaxial tensile behaviour is shown in Fig. 2a. It is observed that with an increase in the current carrying length from 30 to 60 mm (with $J_0 = 35.3$ A/mm^2 and $t_d = 2$ s), instantaneous stress drop increased from 70 to 122.5 Mpa. It is well known that, joule heating increases with increase in the current carrying length hence, higher stress reduction, even though maximum temperature at the centre of the gauge length remains nearly same. It is also observed that temperature gradients are less in specimen with higher current carrying length compared to specimen with lower current carrying length. This can be attributed to internal heat generation in the current carrying length region. This indicates that current carrying length has a significant effect on instantaneous stress drop.

3.2 Effect of Current Density

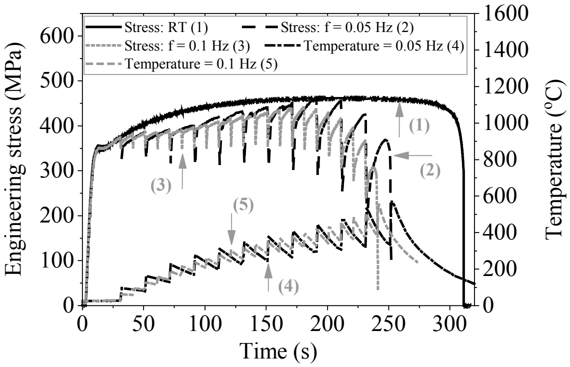
The effect of current density with same energy density in a given time on uniaxial tensile behaviour is shown in Fig. 2b. It is observed that with an increase in the current density from 19.3 to 35.3 A/mm^2, instantaneous stress drop increased from 42.6 to

122.5 MPa. Maximum temperature measured during the tensile test is 190 ± 5 °C and is same for all current densities as energy supplied in a given time is constant. Hence, it can be noted that the temperature rise alone cannot determine instantaneous stress drop. In addition, current density has an independent effect on instantaneous stress drop. Further, high temperature tensile tests are carried out to understand the effect of temperature on flow stress reduction. It is observed that, stress-drop due to electric pulse is significantly higher compared to that of flow stress reduction observed in high temperature tests at similar temperatures.

3.3 Effect of Multiple Current Pulses

Results of multiple pulse experiments indicate that multiple pulses result in both instantaneous stress drop as well as permanent softening in the material. Effect of frequency at constant duty cycle (this ensures the amount of energy supplied to the system is same in a given time) on tensile behaviour and temperature rise is shown in Fig. 3a. Current density of 35.3 A/mm^2 and current carrying length of 60 mm are used in the experiments. It can be noted that the instantaneous stress drop at the time of pulse application is high for low frequency compared to that of high frequency. This can be attributed to increase in energy associated with each pulse as frequency decreases at constant duty cycle (increases the pulse duration). It is also observed that flow stress at any given time during the process is low at high frequency compared to low frequency as shown in Fig. 3a. This can be attributed to less heat dissipation time available when electric pulses are applied at high frequency with same duty cycle. Above observation indicates that use of effectiveness of applying high frequency electric pulses during metal forming processes to achieve load reduction with less temperature rise.

Figure 3b shows the variation of stress and temperature rise during tensile test with multiple pulses at different current carrying lengths. Frequency of 0.05 Hz and current density of 35.3 A/mm^2 are used in the experiments. It is observed that instantaneous stress drop is high for higher current carrying length as soon as each pulse is applied and it is due to higher joule heating. It is clear from Fig. 3b that the amount of permanent softening is more in lower current carrying length specimen. This can be attributed to the deformation zone (gauge length) because of confining the flow of current through deformation zone results in higher reduction at low temperatures. Temperature profiles (Fig. 3b) show that temperature rise after the application of first pulse is same for different current carrying lengths. However, temperature rise will not be the same after the first pulse, due to availability of more area (outside current carrying length) for heat dissipation through conduction to other regions of specimen (no internal heat generation) in lower current carrying length.



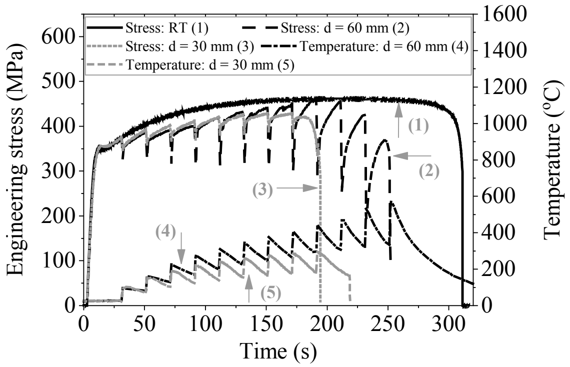


Fig. 3 **a** Effect of frequency and, **b** effect of current carrying length on tensile behaviour and temperature

4 Conclusions

In the present study, electric pulse aided uniaxial tensile tests are carried out on modified specimens with a provision to apply electric current through constrained deformation zone to reduce the overall joule heating. Experiments show that the modified specimens have same stress strain behaviour as standard specimen. Experimental results indicate that current carrying length has a significant effect on instantaneous stress drop i.e., with an increase in the current carrying length the instantaneous stress drop increases. It is also observed that current density has an independent effect on stress drop. Multiple pulse experiments at different frequencies indicate that passing the current through deformation zone is advantageous.

Acknowledgements Authors would like to thank MHRD (GoI), DHI (GoI) and TATA STEEL for the financial support under Uchchatar Avishkar Yojana (UAY). Authors would also like to thank Dr. Rajesh Korla, Department of Materials Science and Metallurgical Engineering, IIT Hyderabad for allowing us to use high temperature tensile test facility.

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