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Leveraging transient mechanical effects during stress relaxation for ductility improvement in aluminium AA 8011 alloy

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ABSTRACT

The mechanical behaviour during stress relaxation of metals has generated considerable interest in the recent years owing to its contribution to ductility. Most of the past studies were focused on ferrous alloys. In the present work, an attempt is made to systematically quantify the improvement in ductility during stress relaxation in AA 8011 aluminium alloy. Room temperature uni-axial tensile tests with single relaxation step were performed under different combinations of pre-strain, strain rate and relaxation time. The ductility was found to increase in all the cases. The parametric dependence of ductility improvement can be assessed using an empirical equation. It was found that the ductility improvement in aluminium is significant compared to SS 316 under similar conditions. The stress-time data obtained is modelled using a recently proposed logarithmic law and is found to fit the experimental data well. The underlying transient mechanisms responsible for ductility improvement are explored by conducting image based fractography analysis of the samples post failure. The fractography was complemented with nano-indentation technique to characterize the homogenization of internal stress.

1. Introduction

Several technological advancements such as hydroforming, high velocity forming, incremental forming and servo press has been developed over the past decades to improve the formability of sheet components. The use of servo press is attractive for immediate application as it does not require any significant changes in the component and tool design. Osakada et al. (2011) reviewed different applications of sheet metal forming and showed that the use of servo press improves the formability and reduces the spring back of sheet components.

Hariharan et al. (2013) and Yamashita and Ueno (2013) have shown that the stress relaxation phenomenon in materials has a major contribution in the formability improvement using servo press. Since then, efforts have been made to systematically quantify the contribution of stress relaxation in ductility improvement through uni-axial tensile tests. The first report in this regard by Hariharan et al. (2013) compared three different steel materials, low carbon steel, dual phase steel (DP) and transformation induced plasticity (TRIP) steels and has shown that the improvement is pronounced at high pre-strain, strain rate and longer hold time. While all the materials exhibited better ductility when the test was stopped intermittently for a given time interval in the uniform deformation zone, its dependence on the influencing parameters were distinctly different. The work hardening mechanisms operating in the respective materials were used to explain this difference. Similar improvements in other materials such as titanium (Eipert et al., 2014) and stainless steel (Li et al., 2017) have been reported. All the studies discussed so far used multiple relaxations in the uniform deformation zone, perhaps assuming that single stress relaxation may not yield measurable improvement. Preliminary tests by Hariharan et al. (2013) in low carbon steel showed that the ductility does not improve linearly with the number of multiple relaxation steps. Subsequent study in SS 316 by Hariharan et al. (2016) showed that single relaxation step is sufficient to obtain noticeable improvement in ductility.

The stress relaxation test has been widely used in the past to determine the metallurgical parameters related to plastic deformation. The stress drops continuously with time and the stress – time relation has been used to estimate the activation volume (Wang et al., 2015), long range internal stress (Trojanová and Lukáč, 2011) and other rate dependent viscoplastic constitutive relations (Krempl and Khan, 2003). However, the structural changes and microscopic mechanisms that occur during stress relaxation have been largely ignored. Understanding these mechanisms is essential to correlate the stress relaxation behaviour with ductility improvement. Recently, Hariharan et al. (2016) propounded two simultaneously operating mechanisms which results in ductility improvement, namely (i) annihilation of mobile dislocations

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and (ii) homogenization of the internal stress, which is supported by the results reported by Varma et al. (2017).

In the present work, the mechanical response of AA 8011 when subjected to stress relaxation under uni-axial isothermal tensile deformation is studied. The objective of the study is two-fold: to verify the effect of stress relaxation on ductility improvement in AA 8011 and to verify the recent hypothesis towards the mechanisms responsible for ductility improvement. As explained above, the stress relaxation studies on ductility improvement has not been studied so far in aluminium or its alloys.[1] Single step stress relaxation is studied by intermittent stopping of the uni-axial tensile tests and the effect of strain, strain rate, holding time are elucidated. The ductility improvement in the present work follows the general trend observed in other materials (Hariharan et al., 2016, 2013). An empirical relation is developed using regression analysis to quantify the parametric influence of contributing factors. The relation is used to compare the ductility improvement in different materials. The transient stress drop with time is modelled using a modified logarithmic equation proposed recently by Hariharan et al. (2016) and found to fit the experimental data very well. Fractography analysis of the samples failed subsequent to stress relaxation were analysed to explain the underlying mechanisms. The fractography analysis was found to be insufficient to explain the stress homogenization and hence additional experiments on Indentation size effect (ISE) using nano indentation were performed to complement the fractography analysis.

2. Experimental study

Cold rolled and soft annealed AA 8011 (O) sheets (Al-98.3, Fe-0.771, Si-0.581) wt.(%) of 1 mm thickness were used as the primary material. Tensile specimens were cut from the center of sheet to avoid rolling-induced edge effect. The wire cut tensile specimens prepared along the rolling direction were annealed at 300 °C for 90 min to relive the residual stresses. Uni-axial tensile tests were performed at different strain rates ($5e^{-3} \le \dot{\varepsilon} \le 2e^{-2}$) following ASTM: *E*8 standard. Stress relaxation tests were performed by intermittent stopping of the tensile test at a fixed pre-strain (ε_0). The pre-strain is normalized with the uniform elongation (plastic strain at ultimate tensile strength) at the corresponding strain rate and expressed as percentage of ε_{UTS}. Parametric studies were conducted by varying the initial strain rate, pre-strain and relaxation time (Table 1). The experiments were performed using Shimadzu 50kN universal tensile testing machine with contact type edge extensometer. All the tests were repeated at least three times for statistical significance.

The specimens subjected to stress relaxation were further deformed under uniaxial tensile load at the initial strain rate till failure. The characteristic features of tensile fracture surface were analyzed with the help of Scanning electron microscope (SEM). Fractographs were processed through image processing software *image j* (Das and Tarafder, 2008) and analyzed to estimate the void fraction. To compare the effect of stress relaxation, two samples, with and without stress relaxation were pre-strained (90% of UTS) in the uniform elongation zone. Samples were cut from the uniformly deformed guage section and gently polished as per standard polishing techniques. Indentation size effect (ISE) was studied on these samples using ASMEC's Universal Nano-mechanical Tester (Bautzner Landstrae 45, Germany) equipped with Berkovich diamond indenter (tip radius ≈184 nm). The indentation test performed in Continuous Stiffness Mode at 100 mN load with a loading and unloading rate of 1 mN/s and hold time of 12 s. The indents were located at the center of the grains to avoid boundary effects.

[1] There were several past studies published on the stress relaxation behaviour of aluminium and its alloys, for instance (Hart and Solomon, 1973; Solberg and Thon, 1985; Sargent and Conrad, 1970; Koleshko et al., 1986). However, the objective of those studies were to estimate the activation parameters and not on ductility improvement.

Table 1
Experimental parameters used in the present study.

Strain rate (s^{-1})	100 * $\varepsilon_0/\varepsilon_{UTS}$(%)	Time (s)
$5e^{-3}$	30, 90	10, 30, 60
$5e^{-3}$, $1e^{-2}$, $2e^{-2}$	50	30

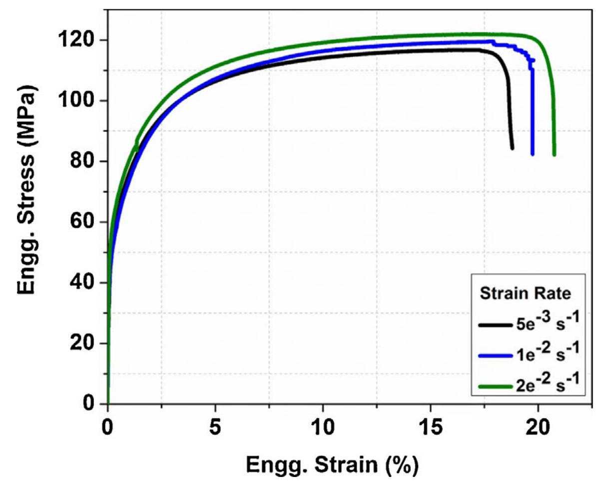

Fig. 1. Monotonic Engg. stress–strain curves for sample tested at different strain rates from $5e^{-3}$to $2e^{-2}\,s^{-1}$.

3. Results and discussion

The engineering stress strain curve obtained from monotonic tensile test at different strain rates is shown in Fig. 1. The flow stress of the material did not show significant variation with strain rate, as reported in similar other alloys of aluminium (Lademo et al., 2010). Stress relaxation tests were performed at different pre-strains in the uniform elongation zone (ε_{UTS}).

3.1. Ductility improvement

The overall ductility of the deforming sample increased when interspersed with a single stress relaxation relaxation cycle. It is observed from Fig. 2 that the ductility increment in the presence of stress relaxation is consistent under different combination of test parameters. All the samples shown in Fig. 2 were subjected to a monotonic strain rate of $5e^{-3}\,s^{-1}$ prior relaxation and a hold time of 30 s during relaxation. The ductility improvement due to stress relaxation in uni-axial tensile test is quantified using a strain ratio, $\epsilon_r = \frac{\epsilon_{relax}}{\epsilon_{mono}}$ where ϵ_{relax} and ϵ_{mono} refers to the true uniform elongation with and without stress relaxation.

The uniform elongation under monotonic tensile test is influenced by temperature and strain rate. The use of strain ratio normalizes the temperature and rate effect and enables the quantification of ductility improvement due to relaxation. While the tensile data is presented (Fig. 1) using engineering stress and engineering strain to include the post uniform-elongation, the elongation improvement ϵ_r is reported in terms of true plastic strain. The improvement in ductility during stress relaxation is maximum at high strain (Fig. 3a), larger hold time (Fig. 3b) and high strain rate (Fig. 3c). The present research findings are consistent with the previously published report on single step relaxation (Hariharan et al., 2016). It may be observed (Fig. 4) that the effect of hold time is pronounced at high pre-strain when compared to that at lower pre-strain. The effect of hold time on different pre-strain is not reported in the earlier studies. This observation supports the mechanisms proposed in the previous work Hariharan et al. (2016), where the homogenization of internal stress plays a major role in the ductility improvement. It is known that the internal stress distribution within a