A study of the influence of stress relaxation on ductility improvement of Ti-6Al-4V alloys

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Abstract

The transient mechanical behavior of materials during stress relaxation has evoked interest in manufacturing applications because of the effect of stress relaxation on formability enhancement. However, most of the previous studies have focused on advanced high strength steels and aluminum alloys. Limited transient stress relaxation studies have been conducted on titanium alloys in order to understand the influence of stress relaxation on forming behavior. Titanium alloys are widely used in aerospace components because of their high strength to weight ratios and excellent fatigue strengths. However, room temperature formability of Ti alloys is an important concern, which restricts their widespread use in various applications. To address these challenges, the present study is aimed to understand the role of transient stress relaxation on formability of Ti alloys. Toward this end, stress relaxation of a dual phase titanium alloy (Ti-6Al-4V) has been investigated experimentally. Stress relaxation tests were performed by interrupting uniaxial tensile tests in the uniform deformation regime for a pre-defined strain and hold time after which tests were continued monotonically until fracture. Single step, room temperature stress relaxation experiments were performed systematically to study the effect of hold time, pre-strain, and strain rate on mechanical properties. The stress relaxation phenomenon was found to contribute positively to the ductility improvement. The mechanisms responsible for enhancing the formability are discussed. The experimentally obtained stress vs. time data were analyzed using a advanced constitutive model for stress relaxation available in literature.

Keywords: Titanium alloys, Stress relaxation, Formability, Ductility

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1. Introduction

Titanium alloys are widely ~~been~~ used in aerospace, biomedical, automotive industries due to excellent corrosion resistance, with good strength to density ratio, and fatigue strength [1, 2]. However, these alloys exhibit poor room temperature formability because of limited slip systems. To improve the formability of these alloys, several metal forming technologies have been proposed. These include hydroforming[3], incremental sheet metal forming [4], electric assisted forming [5], servo press technology [6], which are often utilized to improve the formability. The stepped punch travel in the servo press postpones the failure and improves the room temperature formability [6]. Among these forming techniques, servo press technology has gained attention because it offers improved formability, energy savings, and high productivity [6]. Improved formability has often been attributed to the stress relaxation phenomena [7]. A typical stress relaxation test is carried out by interrupting the test at a pre-determined strain in the uniform plastic deformation regime without unloading the specimen. Thus, a total strain constancy is imposed in the specimen. More often, stress relaxation test is a widely used transient test for estimating deformation parameters like activation volume[8, 9] and internal stress [9]. In recent years, stress relaxation is being actively used as a non-conventional forming technique which tends to postpone the failure and improve the uniform elongation [10, 11]. Most of these studies has been performed on various ferrous alloys [11–13], aluminum [10] and commercially pure titanium (Cp-Ti) alloys [14]. Most of the earlier studies were on multiple relaxation. Later on, it was shown that even single relaxation is effective in improving the uniform elongation. Consequently, several single relaxation studies have been performed [10, 15, 16]. Improvement in ductility was explained by two competing parallel mechanisms, namely (i) dislocation annihilation and (ii) internal stress homogenization [15].Later on, Varma et al. [17] used a combination of nanoindentation and fractography studies of failed specimens to prove the above hypothesis. Previous studies on stress relaxation behavior of titanium alloys focused on estimation of thermally activated deformation parameters. The stress relaxation behaviour of dual phase titanium alloy from ductility improvement perspective is less understood. Therefore, a systematic study is required to elucidate the influence of stress relaxation on the deformation behaviour of dual phase titanium alloy. In the present work, single step uniaxial, isothermal stress relaxation tests were performed on dual phase titanium alloy. The goal of the study is to determine the effect of the relaxation strain, strain rate, and relaxation time on ductility improvement. As explained earlier, stress vs time is one of the main outputs of the test. Often, the stress relaxation is modelled using Orowan equation [18]. The variation in mobile dislocation density during relaxation is long known. Over the years, several stress relaxation models were proposed, but none of the models seems to be accurate. This led to improved models that account for the reduction of dislocation density during relaxation [15, 19]. Recently, all the available and widely used models were compared and reviewed [20]. It was explicitly shown that the recently proposed constitutive model by Varma et al. [21] ~~modelling~~ the stress relaxation behavior.

Therefore, the objective of the present work is to investigate the effect of interruption strain, strain rate and relaxation time on the stress relaxation behaviour of Ti-6Al-4V alloys. A second objective of the work is to model the relaxation behavior using the recently proposed constitutive model[21].

2. Experimental study

In the present investigation, dual phase Ti-6Al-4V sheet with nominal sheet thickness of 2 mm was used as testing material. The chemical composition (in wt.%) of the alloy is Ti 89.5, Al 6.05, V 4.02, Fe 0.228, W 0.0557, Nb 0.0379, and C 0.0280. The samples were prepared along the rolling direction as per ASTM: E8 standard [22]. Stress relaxation tests were conducted using a Zwick/Roell Z100 100 kN [1].universal tensile testing machine equipped with an optical non-contact video extensometer. The experimental test matrix used in the present work is summarized in the Table1. For microstructural investigation of the initial as-received material, the sample was polished as per the standard metallographic procedures, thereafter the sample was etched with Kroll's reagent for 10 s.

[1]Certain commercial equipment, instruments, software or materials are identified to describe a procedure or concept adequately. Such identification is not intended to imply recommendation, endorsement or implication by NIST that the equipment, instruments, software or materials identified are necessarily the best available for the purpose.

Table 1: Experimental matrix used in the present study

Strain rate (s^{-1})	Relaxation strain	Time (s)
$5e^{-3}$	0.9	10
$5e^{-3}$	0.9	30
$5e^{-3}$	0.9	60
$5e^{-3}$	0.3	30
$5e^{-3}$	0.5	30
$1e^{-2}$	0.5	30
$2e^{-2}$	0.3	30
$2e^{-2}$	0.5	30
$2e^{-2}$	0.9	30

3. Results and discussion

The optical microstructure of as received alloy is shown in Figure.1. The microstructure comprises primary α_p and secondary α_s phases in the form of fine lamellae in the prior β phase.

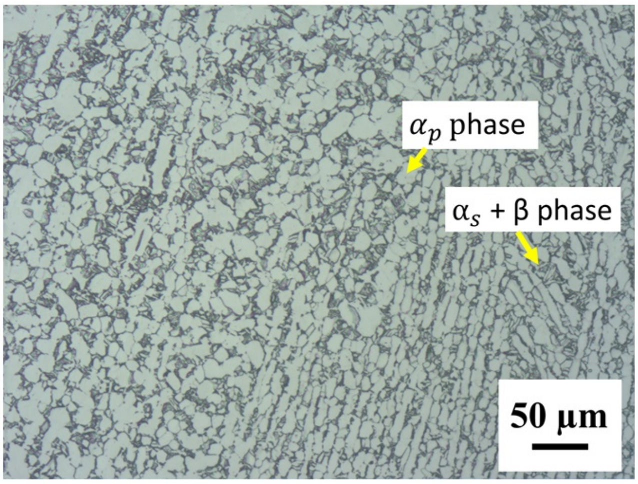


Figure 1: Microstructure of as received Ti–6Al–4V alloy

3.1. Ductility improvement

Both uniform and total elongation of material were improved when tests were performed at different pre-strains in the uniform elongation zone (ε_{UTS}) as shown in Figure 2. The improvement in ductility is estimated using $\varepsilon_r = \frac{\varepsilon_{relax}}{\varepsilon_{mono}}$ where, ε_{relax} and ε_{mono} refers to the true uniform elongation with and without stress relaxation, respectively. It is observed that the improvement in ductility is significant when interruption is performed close to ultimate tensile strength (UTS) (Figure 3 (a)), with larger relaxation time (Figure 3 (b)) and at increased strain rate (Figure 3 (c)). The results of the present study are in line with the previously reported results on single relaxation [10, 15]. From these results, it is clear that relaxation time has more effect when stress relaxation was performed at higher pre-strain. This is due to the fact that in a typical polycrystalline material, the tendency/potential of internal stress homogenization is high at larger pre-strain [23].

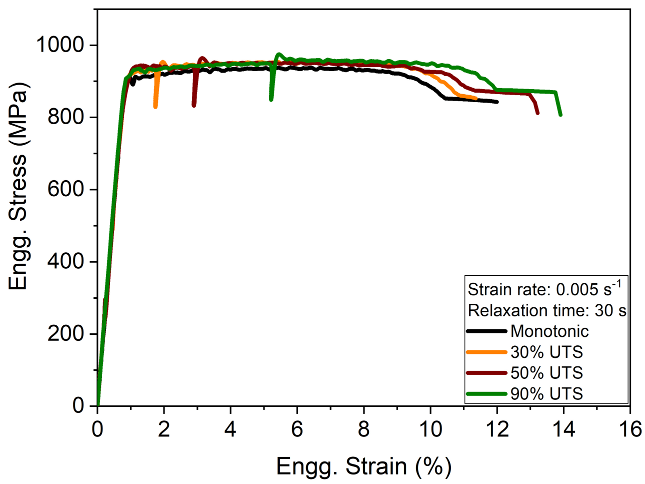
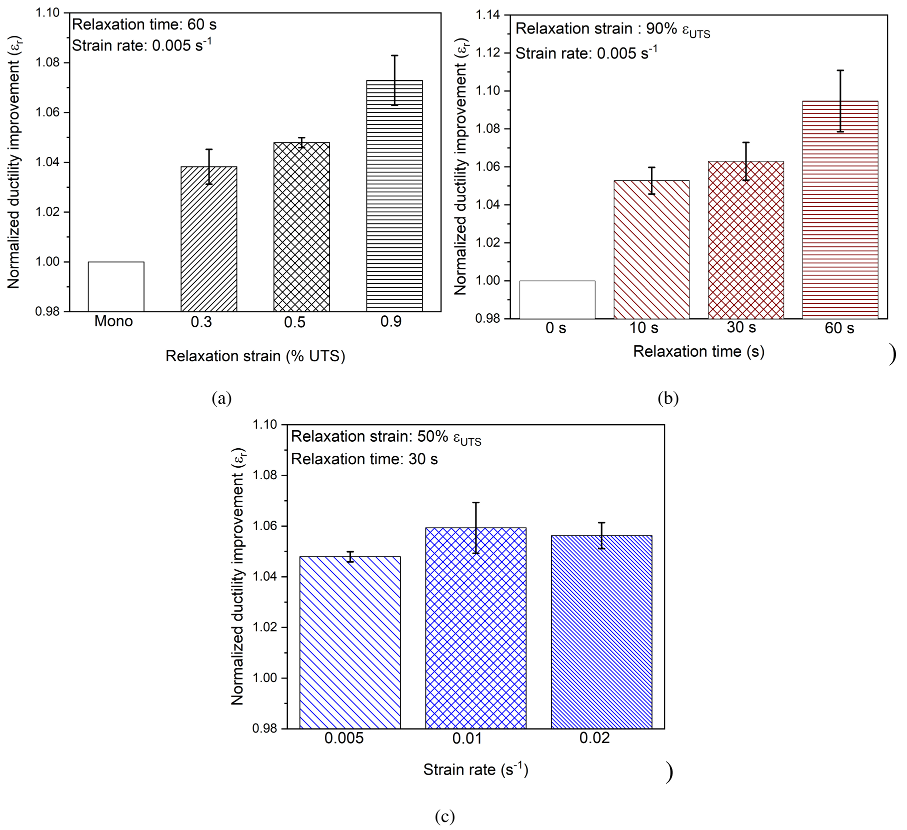
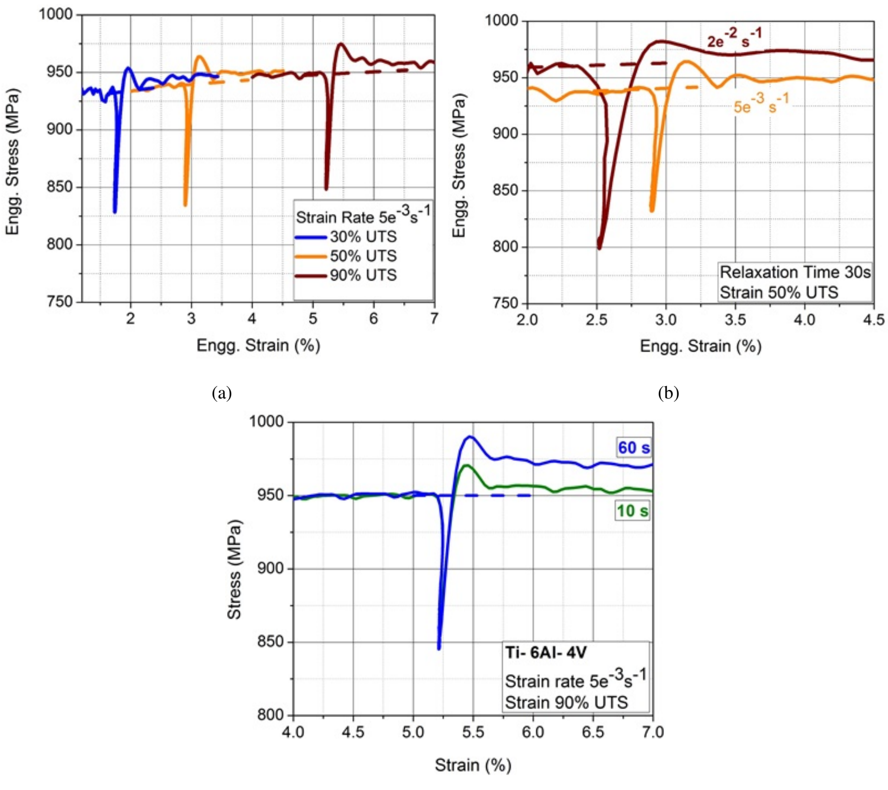


Figure 2: Stress-strain curve for sample subjected to stress relaxation at various pre-strain for 30 s hold time



(a) (b) (c)

Figure 3: Ductility improvement due to stress relaxation showing the effect of (a) Pre-strain, (b) Relaxation time (c) Strain rate



(a) (b)

(c)

Figure 4: Stress jump post relaxation showing the effect of (a) Pre-strain, (b) Strain rate, (c) Relaxation time

The stress-strain response of the material after relaxation is shown in Figure 4. Post relaxation, an increase in stress is observed where the material no longer follows the initial curve, but after a certain plastic strain it follows the original curve. This behaviour is termed reloading yield point phenomena. which occurs when the test is resumed after relaxation. During the stress relaxation, exhaustion of mobile dislocations takes place. As a result, the average mobile dislocation density decreases. The decrease in dislocation density during stress relaxation has been confirmed in several studies [19, 24]. When the material is reloaded, the restoration of exhausted dislocation takes place. Because of this, there is a brief rise in the stress value for a short duration. The flow stress in material increases and reloading yield effects are observed. The yield effects after reloading was found to be a function of strain, strain rate and relaxation time. Similar trend was also observed in SS 316 by Hariharan et al. [15].

3.2. *Stress drop during relaxation*

During stress relaxation, stress continues to drop at constant strain until the material is reloaded. The difference between the true stress value at the beginning and end of relaxation is termed as stress drop, $\Delta\sigma = \sigma_i - \sigma_f$ where,σ_i and σ_f are the stresses in the beginning and at the end of the relaxation cycle.

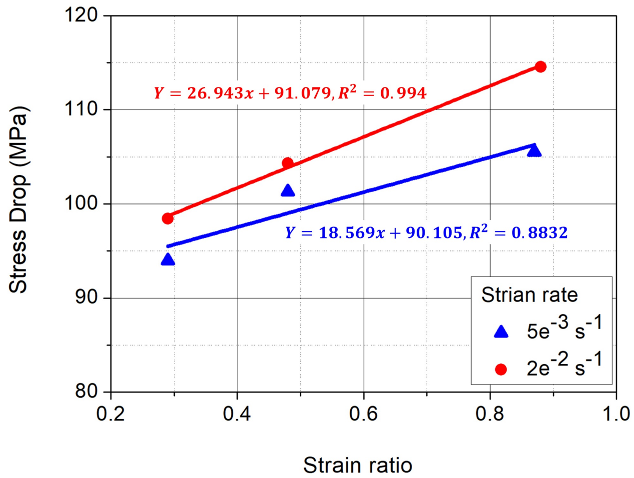


Figure 5: Stress drop during relaxation in Ti-6Al-4V alloy (Relaxation time = 30 s)

Figure.5 shows the stress drop against the normalized strain ratio. The strain ratio is the ratio of interruption strain to the strain at UTS. The stress drop in a material during relaxation is inversely related to the rate of change of average dislocation velocity. The average velocity of dislocations reduces rapidly when the dislocations encounter obstacles. Possible obstacles are second phase (β), precipitates, grain boundaries etc. These obstacles hinder the path of dislocation motion. In other words, the stress drop in a material during relaxation is microstructure dependent. In case of $(\alpha+\beta)$ dual phase alloy such as Ti-6Al-4V, the β phase act as barriers to the dislocation motion. From Figure.5 it is observed that the stress drop $\Delta\sigma$ increases with normalized strain ratio. This phenomena can be explained as follows. The dislocation density in a material increases with an increase in deformation. However, the volume fraction of the β phase remains constant. At lower strain, the dislocation density is less and therefore, the mean free path of dislocations is comparatively high. This results in having a higher dislocation velocity and a lower value of stress drop. At higher values of strain, the dislocation density increases resulting in lower values of mean free path of dislocations and consequently, lower dislocation velocities. This results in larger values of stress drop at higher strain levels. It may be noted that the slope of stress drop with strain ratio is higher at strain rate $2e^{-2}$ compared with that at the strain rate of $5e^{-3}$. The increase in slope is related with the enhanced work hardening at higher strain rate. The above trend of stress drop follows a similar trend as observed in DP steels [12], where the hard martensite phase acts as dislocation barriers.

3.3. Modelling stress relaxation

During a stress relaxation test, the total strain is kept constant. ($\varepsilon_{total} = \varepsilon_e + \varepsilon_p = \mathrm{C}$). The plastic strain rate continuously decreases during relaxation. This can be modelled using Orowan equation, $\dot{\varepsilon}_p = \phi b \rho_m v$; where ϕ is a constant, b is Burgers vector, ρ_m is mobile dislocation density and v is average dislocation velocity [18]. Recently, Varma et al. [21] proposed an advanced constitutive model for stress relaxation. The proposed model overcomes the limitations of the existing models, which is reviewed in [20]. In this model, mobile dislocation density (ρ_m) variation is represented as $\frac{\rho_{m(t)}}{\rho_{mo}} = (\frac{a}{t+a})^{\lambda}$. where, λ and 'a' refers to the rate of dislocation annihilation and fitting constant, respectively. The new model is represented as

$$\sigma_0 - \sigma = \bar{\alpha} \ln \left[1 + \bar{\beta} \left\{ \left(\frac{t+a}{a} \right)^{1-\lambda} - 1 \right\} \right] \tag{1}$$

where, $\alpha = kT/V^*$, $\overline{\beta} = E \phi b \rho_{mo} \frac{V^*}{kT} \frac{a}{1-\lambda} exp\left(-\frac{\Delta G_0 - \sigma_0^* V^*}{kT} \right)$ and σ_0^* refers to the effective stress at the beginning of relaxation at $t = 0s$. In the present study, the above stress relaxation model (eq.1) is used to fit the experimental stress relaxation data using the least square fitting method. The coefficient of determination, R^2, of the fit is 0.98. The advanced model ~~found~~ to fit the experimental data very well, as shown in Figure 6. The parameters of the model are tabulated in Table 2

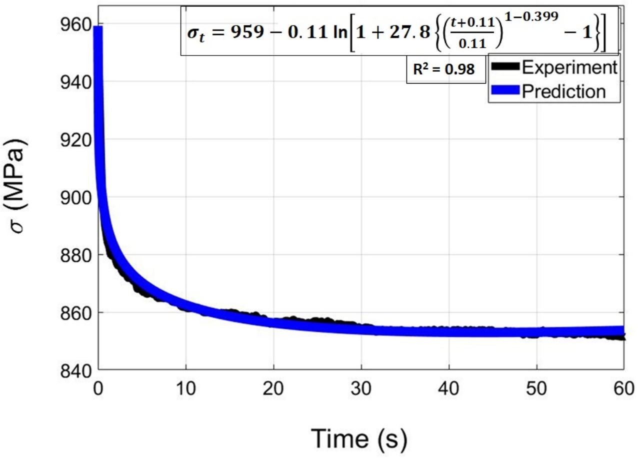


Figure 6: σ vs t predicted using equation (1)

Table 2: Parameters of advanced constitutive model

$\dot{\varepsilon}$ (s^{-1})	ε (% UTS)	t(s)	a	$\bar{\alpha}$	$\bar{\beta}$	λ
$5e^{-3}$	90	10	0.11	13	27	0.329
$5e^{-3}$	90	30	0.11	12.8	27.8	0.399
$5e^{-3}$	90	60	0.11	12.5	27.8	0.399
$5e^{-3}$	30	30	0.11	14.5	27.8	0.559
$5e^{-3}$	50	30	0.11	14.6	28.1	0.599
$1e^{-2}$	50	30	0.12	14.8	28.3	0.610
$2e^{-2}$	30	30	0.13	14.9	27.6	0.622
$2e^{-2}$	50	30	0.14	15.2	28.8	0.730
$2e^{-2}$	90	30	0.14	15.4	28.9	0.747

4. Conclusions

The main objective of this study was to explore the effect of stress relaxation phenomenon in the dual phase ($\alpha + \beta$) Ti-6Al-4V alloy. Following conclusions can be drawn from the present work.

1. Significant improvement in ductility is obtained using single step stress relaxation. The improvement is found to depend on strain, strain rate, and relaxation time.

2. Stress drop during relaxation increases with relaxation strain and increases with strain rate of deformation, which is related with the strain hardening rate.
3. A recently proposed constitute model [21] was found to fit the experimental data very well.

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