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Effect of Prior Cold Work on Tensile Flow and Work Hardening Behavior of a Titanium Bearing Modified Austenitic Stainless Steel

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Abstract. The tensile flow and work hardening behavior of 14Cr-15Ni-2.2Mo-Ti austenitic stainless steel at 298 K and 973 K with different prior cold worked levels ranging from 16% to 24% were analyzed using the Ludwigson, Swift and Voce constitutive equations. Influence of prior cold work on various Ludwigson parameters is discussed. While the Swift equation is used to predict the prior cold work, the yield strength is estimated using the Voce equation. The work hardening analysis using $\theta\sigma$-σ plot showed stage II hardening in the case of the material without coldwork. A two stage hardening behavior consisting of rapidly decreasing transient stage followed by gradually decreasing stage III hardening is observed at all cold work levels.

Keywords. Prior cold work, work hardening, Ludwigson equation, Swift equation, Voce equation, 14Cr-15Ni-Ti stainless steel.

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1 Introduction

A titanium modified 14Cr-15Ni stainless steel designated as IFAC-1 (Indian Fast Reactor Advanced Core Material) is developed to be used for in-core applications of the Prototype Fast Breeder Reactor which is in an advanced stage of construction at Kalpakkam, India [1]. 20% prior cold work (PCW) is the optimum level of coldwork to be given for swelling resistance of this material. However a tolerance of ±4% is allowed in the degree of cold work that has to be imparted on the material [2]. It is essential to understand the variation of the tensile flow behavior in this tolerance range to predict its performance during service.

Extensive studies have been carried out to understand the tensile flow characteristics of engineering materials using constitutive equations, and to describe the physical significance of the parameters of the equations. The tensile flow behavior in the plastic range can generally be described by Hollomon relation [3]:

$$\sigma = K\varepsilon^n, \tag{1}$$

where σ, ε are the true stress and the true plastic strain respectively. K is the strength coefficient and n is the strain hardening exponent. Face Centered Cubic materials having low stacking fault energy generally do not follow the Hollomon equation at low strains. Taking this deviation into consideration, Ludwigson proposed the following modification of Hollomon equation [4]:

$$\sigma = K_1\varepsilon^{n_1} + \exp(K_2 + n_2\varepsilon), \tag{2}$$

where K_2 and n_2 are additional constants.

The flow behavior for pre-strained material can be described by the Swift equation [5]:

$$\sigma = K(\varepsilon_0 + \varepsilon)^n, \tag{3}$$

where ε_0 is the measure of the amount of pre-strain in the material.

Voce equation can be used for analyzing tensile flow behavior when the stress tends to saturate at large strains [6].

$$\sigma = \sigma_s - (\sigma_s - \sigma_1)\exp\left(-\frac{\varepsilon_c - \varepsilon_1}{\varepsilon_c}\right), \tag{4}$$

where σ_s is the saturation stress, σ_1 is the stress at the start of plastic strain ε_1, the value of ε_1 is usually set to 0 and ε_c is a characteristic strain constant. By setting $n_v = -1/\varepsilon_c$, equation (4) reduces to

$$\sigma = \sigma_s - (\sigma_s - \sigma_1)\exp(n_v\varepsilon). \tag{5}$$

It has been earlier shown that for the material with a similar composition in solution annealed condition as of that used in the present study, the flow behavior could be described by Voce equation at temperatures in the range 300 to 1023 K [7]. Ludwigson equation could be used to model the flow curve for temperatures up to 923 K. Samuel et al. [8]

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showed that the Swift equation could be used to obtain the PCW level by carrying out tests at 300 K for 316 stainless steel. In this investigation, the influence of PCW on the tensile flow behaviour of IFAC-1 has been assessed by carrying out tensile tests at 298 K and 973 K. The material is expected to experience a maximum temperature of around 973 K during operation in the fast breeder reactor.

2 Experimental

The material used in this analysis (IFAC-1) had the following chemical composition (in mass %) 0.046 C, 14.35 Cr, 15.38 Ni, 2.4 Mo, 2.38 Mn, 0.25 Ti, 0.74 Si, 0.034 P and balance Fe. Primary melting of the ingot was carried out by vacuum induction melting (VIM) followed by refining by vacuum arc remelting (VAR). The ingot was hot forged and rolled down to 12 mm thick plates. These plates were subjected to annealing at 1323 K for 30 min. Rods of 10 mm diameter were machined from these plates. These rods were subjected to cold work of 16%, 18%, 20%, 22% and 24% by tensile pulling at a strain rate of 1.3×10^{-3} s^{-1}. Tensile specimens were fabricated from the coldworked rods as well as from the as-received rods without prior cold work. The tensile specimens had a gauge diameter of 4 mm and a gauge length of 26 mm. Tensile tests where carried out using a screw driven universal testing machine at a nominal strain rate of 3.2×10^{-3} s^{-1} at 298 K and 973 K. Constitutive equations were used for modeling the true-stress true strain data by Lavenberg–Marquardt least square method. The work hardening rate θ, which is used for plotting the $\theta\sigma$–σ graphs was calculated from the true stress- true plastic strain data using the following central difference formula:

$$\theta = \left(\frac{\sigma_i - \sigma_{i-1}}{\varepsilon_i - \varepsilon_{i-1}} + \frac{\sigma_{i+1} - \sigma_i}{\varepsilon_{i+1} - \varepsilon_i} \right) / 2. \qquad (6)$$

3 Results and Discussion

The true stress true strain plots for IFAC-1 for various cold work levels at 298 K and 973 K are shown in Figure 1(a) and (b) respectively. The tendency of the flow behavior to saturate at larger strains is more pronounced at 973 K for all the PCW levels. The double logarithmic plot of true stress true strain behavior at 298 K and 973 K are shown in Figure 2(a) and (b) respectively. The deviation from the Hollomon relationship at lower strains was evident at both the temperatures. Hence this equation is not used to characterize the plastic flow behavior in the present study

3.1 Variation of Ludwigson Parameters With PCW

A typical plot of true stress and true plastic strain fitted using Ludwigson equation is shown in Figure 3. Table 1 gives

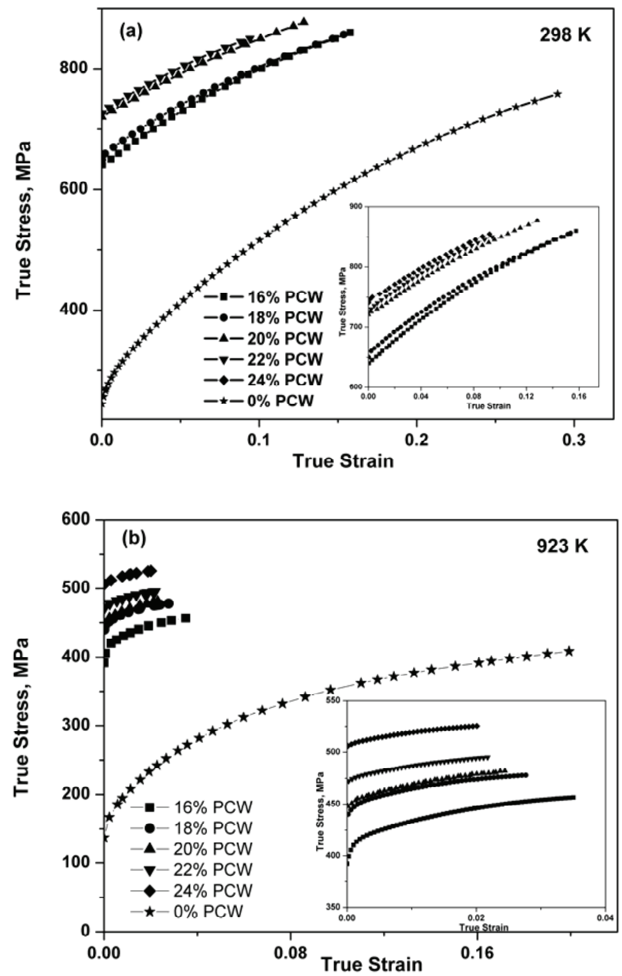

Figure 1. True stress-true strain curve of IFAC-1 with the insert showing the plot for PCW levels of 16%, 18%, 20%, 22% and 24% at (a) 298 K and (b) 923 K.

the values of the Ludwigson parameters along with the χ^2 values. χ^2 is the summation of the squares of the difference between the experimentally determined value and the value in the model. Smaller value of χ^2 corresponds to a better fit. The variations of the Ludwigson parameters are discussed below. In the present study the value of K_1 reduced steadily with increase in PCW at 298 K though the variation of this parameter was not significant at 973 K as shown in Figure 4(a). The parameter n_1 has a strong dependence on PCW at both temperatures. But the dependence of n_1 was more predominant at 298 K. Figure 4(b) shows that with increase in cold work the value of n_1 decreases at both the test temperatures. The values of K_2 did not show any distinct trend with change in PCW at both the temperatures (Figure 4(c)). However the absolute values of n_2 increased steadily with PCW at 298 K. The absolute values of n_2 were much higher at 973 K than at 298 K as shown in Figure 4(d). The value ε_L which can be obtained from the Ludwigson equation, is the transition strain above which only cross-slip

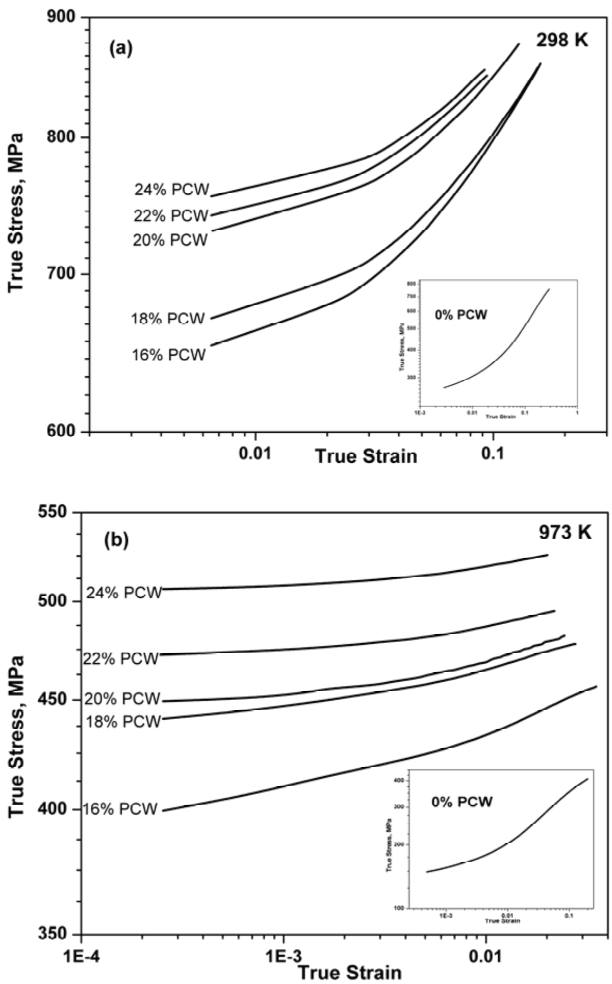

Figure 2. Double logarithmic plot of true stress-true strain curve of IFAC-1 with the insert showing the plot for 0% PCW at (a) 298 K and (b) 923 K.

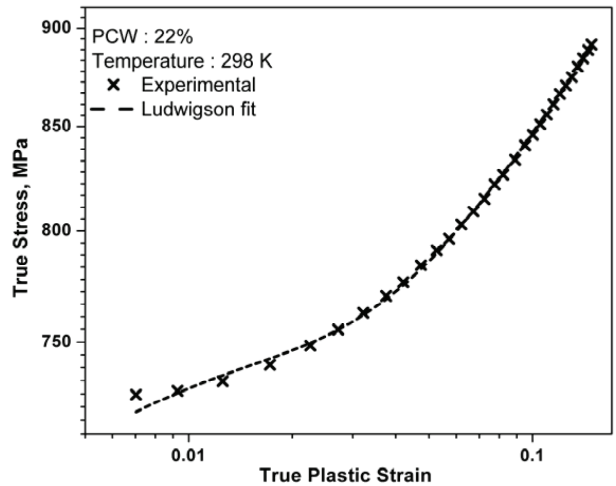

Figure 3. True stress-true plastic strain plot of 22% PCW material at 298 K fitted with Ludwigson equation.

occurs [4]. The value can be obtained by setting the ratio r to 0.005. The ratio r can be defined as:

$$r = \exp(K_2 + n_2\varepsilon)/K_1\varepsilon^{n_1}. \tag{7}$$

Figure 4(e) shows that the value of ε_L decreased with increase in PCW at both the temperatures.

The Ludwigson parameter K_1 is the strength coefficient and denotes the ability of the material to strengthen by deformation. The possible reason for the decrease in the value could be that the amount of plastic deformation possible decreases with increase in PCW. Such a trend in the values of K_1 with PCW has already been reported by Samuel [9]. The parameter n_1 which can be taken as the strain hardening exponent as in the Hollomon equation is dependent on the Ti/C ratio. In the present study this ratio is ∼5.4. It has been shown that for Ti/C ratios greater than 4 the values of n_1 decreases when C and N are in solution, and increases with the formation of the precipitates TiC and TiCN [10]. With cold work, secondary TiC phase starts to precipitate by aging at temperatures in the range of 923 to 1173 K, with aging times ranging from 0.25 to 1000 h [11]. However in our study, the Ludwigson parameter n_1 did not increase with increase PCW at 973 K suggesting that the kinetics did not favor the precipitation of TiC [12]. The parameter K_2 is the measure of deviation of the true stress-true strain plot from Hollomon relation [13]. The variation of values of this parameter with PCW was not significant at both temperatures. The parameter n_2 which is negative denotes the rate at which the ratio between the short range and long range stresses reduces with increase in plastic strain [13]. Greater absolute value of n_2 denotes the dominance of long range stress. Larger absolute values for n_2 at 973 K suggests that the transition to long range stresses occurred readily at higher temperatures. Further, increase in PCW enables the transition from short to long range stresses to occur faster. The value of the parameter ε_L decreases with increase in PCW because, increase in the plastic strain decreases the initial range of strain during which planar slip can occur. Thus material with higher PCW has lower strain range for planar slip and transition to cross slip can readily occur. At 973 K, the value was significantly lower, indicating the predominance of cross slip. At high temperatures, the mobility of dislocations increases thereby decreasing the transition strain, ε_L [14].

3.2 Variation of Swift Parameters With PCW

Figure 5 shows a typical plot of true stress vs. true strain fitted using Swift equation. Table 2 shows the values of the Swift parameters at both 298 K and 973 K. The value of the parameter ε_0 in the present study increased with PCW. It was mentioned in equation (3) that the value ε_0 is the measure of pre-strain in the material; however in the

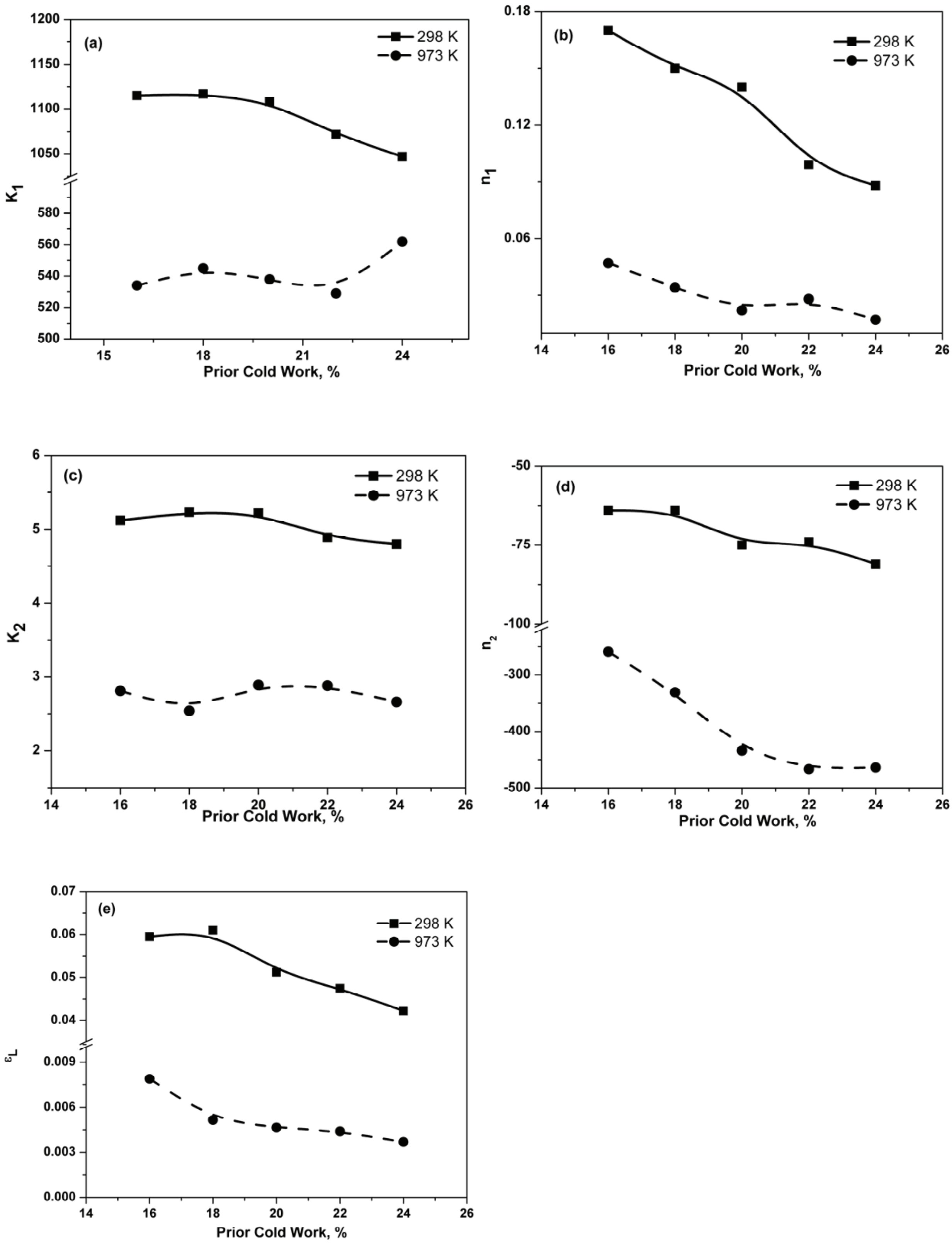

Figure 4. Variation of Ludwigson parameter (a) K_1 (b) n_1 (c) K_2 (d) n_2 (e) ε_L with PCW at teat temperatures at 298 K and 973 K.

Prior cold work (%)	298 K						973 K					
	K_1	n_1	K_2	n_2	ε_L	χ^2	K_1	n_1	K_2	n_2	ε_L	χ^2
0	1208	0.37	4.8	−51	0.0774	4.64	608	0.23	4.12	−381	0.0106	7
16	1115	0.15	5.12	−64	0.0595	0.9	534	0.047	2.81	−259	0.00789	0.11
18	1117	0.14	5.23	−64	0.061	1.07	545	0.034	2.54	−331	0.00515	0.1
20	1108	0.12	5.22	−75	0.0512	6.2	538	0.022	2.89	−434	0.00465	0.005
22	1072	0.099	4.89	−74	0.0475	0.2	529	0.028	2.88	−467	0.0044	0.03
24	1047	0.088	4.8	−81	0.0422	0.26	562	0.017	2.66	−464	0.0037	0.003

Table 1. Parameters derived from Ludwigson equation for test temperatures of 298 K and 973 K.

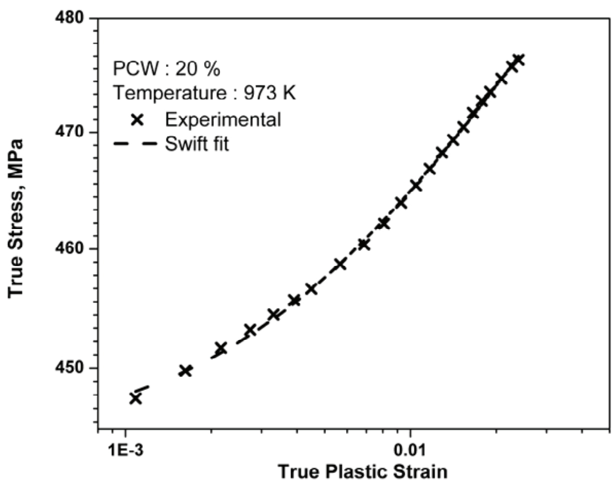

Figure 5. True stress-true plastic strain plot of 22 % PCW material at 298 K fitted with Swift equation.

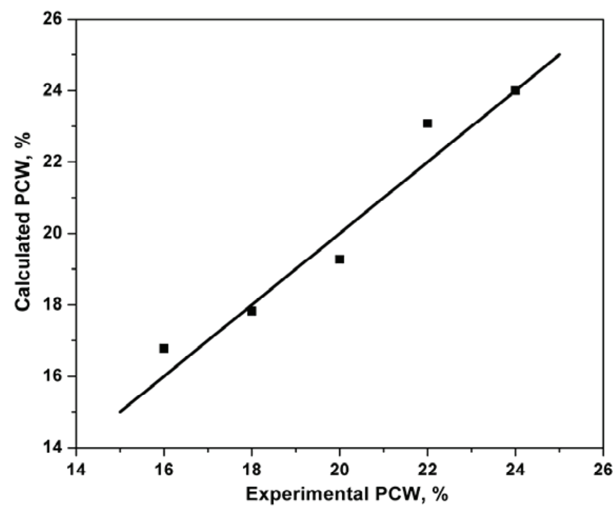

Figure 6. Comparison between actual PCW and the calculated PCW using modified Swift equation.

present study it did not correspond to the exact PCW level. Fernandes et al. [15] have shown that this parameter represents the pre-strain only if there is a uniform change in strain path for multiple loadings. In the present work PCW which was given by tensile pulling, was carried out at a different strain rate when compared to the tensile test. This corresponds to a complex change in strain path. In such cases, a modified Swift equation can be used to describe the strain dependence of flow stress [15]:

$$\sigma = K^*(\varepsilon_0^* + \varepsilon)^n, \quad (8)$$

where $K^* = Kh^n$ and $\varepsilon_0^* = \frac{g}{h}(\varepsilon_0 + \varepsilon_p)$, g represents the alteration of the reloading yield stress after the path change and is equal to 1 in the absence of such changes in strain path; h characterizes the difference in the work hardening behavior between reloading and initial strain path and is equal to 1 in case there is no difference. The value ε_o corresponds to the cold work before the first strain path. ε_p denotes the pre-strain after the first strain path. In the present study, it corresponds to the strain due to PCW. In the as received material with no PCW, ε_o determined experimentally was found to be 0.022 suggesting that there was a small amount of pre-strain even in the mill annealed condition.

An effort was made to estimate the PCW level using the modified Swift equation. Since $g = h = 1$ and $\varepsilon_p = 0$, for the material with no PCW, the value of $\varepsilon_0^* = \varepsilon_0 = 0.022$. The ratio g/h was obtained from ε_0^* value corresponding to 24% PCW, by substituting the value $\ln(1 + 0.24)$ for ε_p. Figure 6 shows that there is an appreciable agreement between the value of the PCW calculated using the modified Swift equation and the actual PCW level.

The strength coefficients and the stress exponents of the Swift and the Ludwigson equation were comparable at 973 K for all the PCW materials. It can be concluded that the effect of PCW characterized by the factor ε_0^* in the Swift equation and the planar slip characterized by the term $\exp(K_2 + n_2\varepsilon)$ in the Ludwigson equation, were negligible at 973 K.

Prior cold work (%)	298 K				973 K			
	K^*	n	ε_0^*	χ^2	K^*	n	ε_0^*	χ^2
0	1254	0.42	0.022	12.85	612	0.24	0.0014	10.54
16	1269	0.27	0.071	0.36	539	0.051	0.0026	0.19
18	1231	0.25	0.074	0.19	552	0.039	0.0027	0.1
20	1218	0.2	0.079	0.13	537	0.033	0.0033	0.07
22	1250	0.23	0.092	0.12	551	0.029	0.0057	0.04
24	1230	0.22	0.095	0.13	572	0.023	0.005	0.02

Table 2. Parameters derived from Swift equation for test temperatures of 298 K and 973 K.

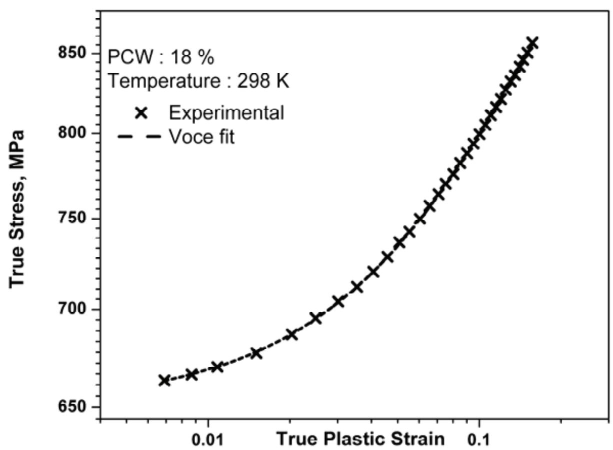

Figure 7. True stress-true plastic strain plot of 18% PCW material at 298 K fitted with Voce equation.

4 Variation of Voce Parameters With PCW

Figure 7 shows a typical plot of true stress vs. true strain fitted using Voce equation. Table 3 shows the various parameters obtained at 973 K and 298 K. The parameter σ_1 corresponds to the stress at the start of plasticity which corresponds to the yield strength of the material. Figures 8(a) and 8(b) show the plots of experimentally determined values of yield strength against the Voce parameter σ_1 at 298 K and 973 K respectively. The values of σ_1 were higher than the yield strength at 298 K. The higher values of σ_1 than the experimentally obtained yield strength values were reported by Girish [16]. However the prediction was more accurate at materials tested at 973 K. Recovery is more significant at 973 K; consecutively there is saturation in stress with increase in strain. Thus the Voce fit is more accurate at 973 K and thus the prediction of true yield strength closely follows the experimental values at this temperature.

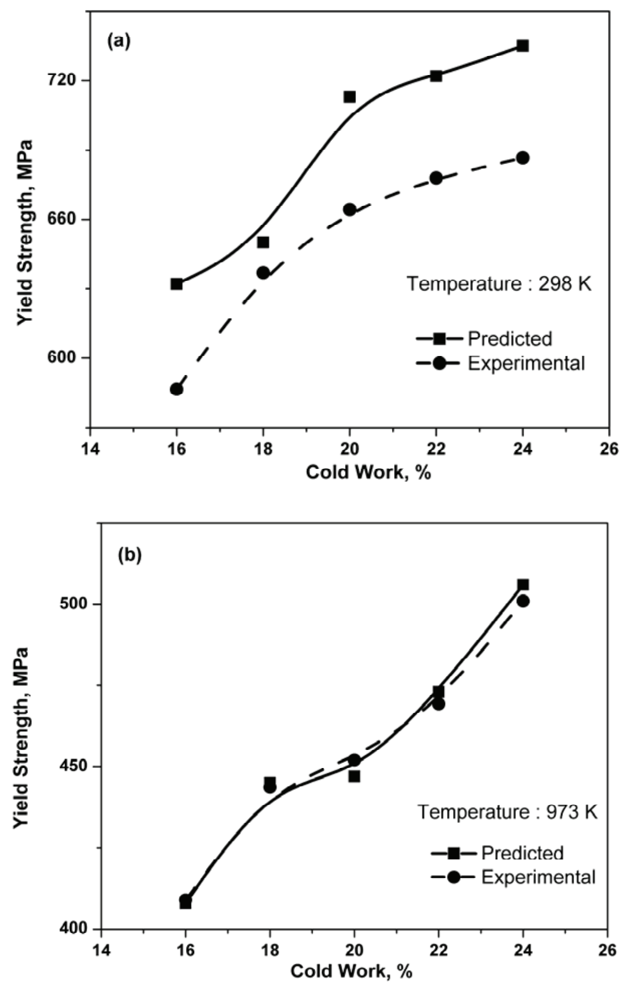

Figure 8. Comparison between the actual yield stress and the predicted yield stress by Voce equation at (a) 298 K (b) 973 K.

4.1 Work-hardening Behavior

Figures 9(a) and (b) show the influence of cold work on $\theta\sigma$-σ plots at 298 K and 973 K respectively. The $\theta\sigma$-σ plot can more distinctly show the difference between stage II and stage III of work hardening behavior than θ-σ plot [17]. The work hardening behavior for all the materials showed an initial transient stage (TS) where there was a rapid decrease in the work hardening rate. Stage II hardening was observed only with as received material with no PCW at

Prior cold work (%)	298 K				973 K			
	σ_s	σ_1	n_v	χ^2	σ_s	σ_1	n_v	χ^2
0	947	275	−4.3	1.06	415	168	−14	18
16	1038	632	−5.1	0.11	465	408	−50	0.05
18	1018	650	−5.2	0.16	492	445	−56	0.07
20	993	722	−6.5	0.11	483	447	−66	0.01
22	1066	713	−4.7	0.14	501	473	−67	0.08
24	1037	735	−5.3	0.07	530	506	−76	0.05

Table 3. Parameters derived from Voce equation for test temperatures of 298 K and 973 K.

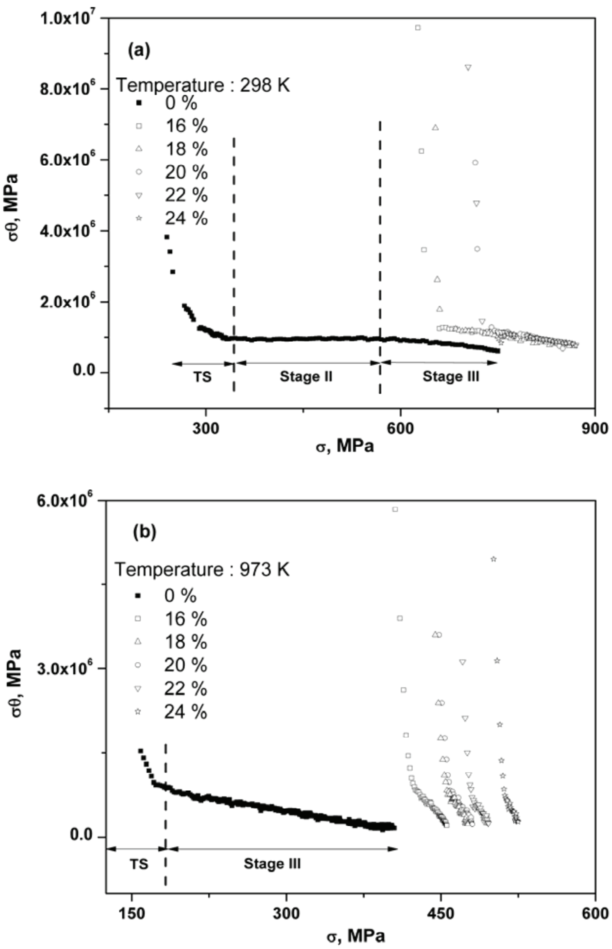

Figure 9. Effect of PCW on $\theta\sigma$-σ plot at (a) 298 K and (b) 973 K.

room temperature. Feaugas [18] showed that in stage II there is a dominance of the intergranular back stresses arising due to the planar dislocation structures like pile-ups and stacking faults. Intergranular back stresses disappear in stage III due to the activation of the cross-slip process. The transition strain ε_L obtained from the Ludwigson equation, above which the planar slip is replaced by cross slip, was the highest in the as received material at room temperature. This could be the reason for the occurrence of stage II. Except for the as received material, the stage III of the work hardening behavior overlapped for all the PCW materials at 298 K. The alteration in strain path which could change the work hardening behavior characterized by the parameter h in the modified Swift equation could be the reason for the small drift in the stage III of the as received material at 298 K.

The rate of decrease of $\theta\sigma$ is higher at 973 K in stage III than the rate of decrease of $\theta\sigma$ obtained at 298 K. Stage III is the recovery stage and it can be associated with the parameter n_v of the Voce equation. The value of n_v can in turn be associated with various mechanisms controlling recovery. For larger absolute values of n_v the slope is higher in stage III. It can be seen that the values of n_v did not show any appreciable variation at 298 K (Table 3). Thus PCW did not influence recovery at this temperature. At 973 K, the absolute values of n_v increased steadily with PCW. For the material with no PCW the value was considerably smaller. This ascertains that PCW accelerates the recovery process. Gottstein and Argon [19] have shown that for lower values of n_v, cross-slip is more dominant; whereas for higher absolute values of n_v, climb and subboundary migrations are more dominant. The contribution for recovery by climb varies as the second power of dislocation density. The increase in PCW also increases the dislocation density thereby contributing to dislocation climb thus increasing the absolute value for n_v.

5 Conclusions

1. The tensile flow behavior of IFAC-I SS was found to be described well by the Ludwigson, Swift and Voce equations, for all PCW levels at both 298 K and 973 K.

2. Cross-slip occurred more easily at 973 K and with higher levels of PCW, as shown by the transition strain ε_L obtained from the Ludwigson equation.

3. The amount of PCW was estimated by the modified Swift equation which could be used for materials undergoing complex strain paths.

4. The yield strength was accurately predicted by the Voce parameter σ_1 at 973 K.

5. Occurrence of stage II work hardening arising in the as received material at 298 K was due to the dominance of planar slip.

6. Higher absolute value of the Voce parameter n_v corresponding to steeper slopes in stage III was due to the increase in climb and sub-boundary migrations with increase in PCW at 973 K.

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