Warm deformation behaviour of P92 steel

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Abstract
The warm deformation behaviour of three P92 steels with different chemical compositions within the ASTM specification was studied. Warm uniaxial compression tests were done using a Gleeble\textsuperscript{®} 3500 thermo-mechanical simulator over a temperature range of 575 °C–650 °C and a strain rate range of 10\textsuperscript{−3}–0.5 s\textsuperscript{−1}. The results show that the flow stress decreased with an increase in the deformation temperature and a decrease in the strain rate. The effects of deformation parameters on the flow stress behaviour were analysed to determine the constants for an Arrhenius constitutive equation. The strain hardening coefficients were 32.0 (P92–A), 31.6 (P92–B) and 39.1 (P92–C). The calculated apparent activation energy values for the three steels were 616 kJ mol\textsuperscript{−1} (P92–A), 751 kJ mol\textsuperscript{−1} (P92–B) and 815 kJ mol\textsuperscript{−1} (P92–C). The variation in the activation energy was attributed to differences in elemental concentration, such as the chromium content. A constitutive model for predicting the flow stress behaviour of the three steels was developed. The statistical parameters: Pearson’s correlation coefficient (R) and the average absolute relative error (AARE) were used to verify the model. From the analysis, the statistical values were: R = 0.987 and AARE = 1.11% for P92-A steel, R = 0.997 and AARE = 0.80% for P92-B steel, and R = 0.99 and AARE = 0.92% for P92-C steel. Therefore, the developed model was able to effectively describe the warm deformation relationship between stress, temperature and strain rate under the investigated test conditions in these three P92 steels.

1. Introduction
Creep resistant steels have been widely used in high temperature power plant applications such as the boiler header [1]. Creep Strength Enhanced Ferritic (CSEF) steels have good creep resistance, high strength, weldability, and fabricability [2, 3]. By increasing the in-service temperature and pressure conditions, the use of these steels has enhanced power plant efficiency and reduced the CO\textsubscript{2} emissions to meet environmental regulations [4, 5]. The most commonly used CSEF steels in the fossil fuel power plants for high temperature use include the ASTM A335 grades P92, E911 and P122 [1, 6]. P92 steel was developed from modified P91 steel by decreasing the amount of molybdenum and adding tungsten. The use of P92 steel has become more prevalent in the fabrication of power plant components such as boiler pipes, headers and reactors [7], as it has higher creep strength under service conditions than P91 steel [8]. This high temperature stability is due to the evolution of stable chromium-containing M\textsubscript{23}C\textsubscript{6} carbides and finely distributed vanadium or niobium containing MX carbonitrides precipitates in the matrix, which impede dislocation movement and creep [9]. However, after prolonged application at high temperature, precipitates which are detrimental to strengthening, such as the Laves Fe\textsubscript{2}(W, Mo) phase, may form [10].

In general, the activation energy for steels affects their hot workability and depends on the chemical composition of the material [11]. P92 steels exhibit complex deformation behaviour due to the many alloying elements [12]. The deformation load increases due to evolution of a number of precipitates during hot deformation which impede dislocation movement [13]. The substitutional elements, such as Mn, Nb, Si, Cr, Mo and W contribute to the flow stress and the addition of chromium increases the activation energy [13]. Vasilyev

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and Golikov [14] found an increase of ∼46% in activation energy when more than 1 wt% Cr was added. Aluminium is reported to delay the initiation of dynamic recrystallisation (DRX) and increase activation energy [15]. The addition of carbon in steels decreases hot working activation energy as it increases the self-diffusion of iron [16]. The change in the activation energy during the deformation process may be attributed to alloying elements and other impurities that affect diffusivity [12]. However, the activation energy only shows the degree of difficulty in the deformation process which is associated with the atomic arrangement of steel [17]. Despite available information on effects of the individual elements on warm deformation behaviour of P92, the effects of small chemical composition variations within the ASTM A335/ASME SA335 P92 specification [18] have not been widely published.

The warm deformation process can be effectively characterised using constitutive models that were developed for hot deformation. Several models quantitatively describe the relationship between deformation conditions and flow stress. The Arrhenius constitutive model (equation (1)) [19] has been widely used to predict the flow stress behaviour of many alloys, including modified 9Cr-1Mo steel [20], and P92 steel [8, 12, 21].

The relationship between flow stress deformation has been given by the Arrhenius equation [19]:

\[ \dot{\varepsilon} = A f(\sigma) \exp\left(-\frac{Q}{RT}\right) \]  

(1)

The stress function \( f(\sigma) \) is the maximum flow stress value and can be expressed as:

- \( f(\sigma) = \sigma^{n'} \) if \( \alpha \sigma < 0.8 \)
- \( f(\sigma) = \exp(\beta \sigma) \) if \( \alpha \sigma > 1.2 \)
- \( f(\sigma) = (\sinh(\alpha \sigma))^n \) for all \( \sigma \)

where \( \dot{\varepsilon} \) is the strain rate \((s^{-1})\), \( Q \) is the thermal activation energy, \( R \) is the universal gas constant, \( T \) is temperature \((\text{in K})\), \( n \) and \( n' \) are stress exponents, \( A \) and \( \beta \) are material constants, and \( \alpha \) is a stress multiplier \((\alpha \approx \beta/n')\) [17, 22].

This study investigates the possibility of using warm deformation to manufacture structural components of P92 steel for power plant applications. The metal flow behaviour of P92 steels was analysed in the warm deformation temperature range using Arrhenius’ equation. From the analysis, constitutive equations for predicting flow stress behaviour of the three P92 steel compositions were developed and verified using statistical error analysis.

Table 1. Chemical compositions of the three P92 steels (in wt.%).

| Steel  | C  | Mn | Si | Cr  | Mo | Ni | Cu | Al | V  | Nb | W  | Co |
|--------|----|----|----|-----|----|----|----|----|----|----|----|----|
| P92–A  | 0.10 | 0.39 | 0.20 | 8.29 | 0.65 | 0.19 | 0.08 | 0.012 | 0.16 | 0.093 | 2.07 | 0.015 |
| P92–B  | 0.11 | 0.51 | 0.22 | 9.37 | 0.50 | 0.17 | 0.27 | 0.006 | 0.19 | 0.130 | 1.76 | 0.028 |
| P92–C  | 0.11 | 0.32 | 0.25 | 9.48 | 0.61 | 0.17 | — | 0.023 | 0.20 | 0.076 | 2.34 | 0.024 |

Figure 1. Thermal profile of the warm deformation tests.
2. Experimental procedure

The chemical compositions of the three steels (named P92-A, B and C) were determined by optical emission spectroscopy and are listed in table 1. The microstructure of as received three P92 steels is shown in figure 2. The three P92 steels exhibited tempered martensitic microstructure with well-defined grain and lath boundaries. The SEM micrographs show precipitates at triple points and along grain and lath boundaries. The precipitates are mainly $M_23C_6$ ($M = Fe, Mo, W, Cr$) carbides and $MX$ ($M = V, Nb; X = C, N$) carbonitrides. These enhance solid solution strengthening by hindering dislocation movement during the deformation process [5]. Rod specimens (8 mm Ø, 12 mm length) were machined from each of the three ASME P92 steel blocks.

| Table 2. Warm compression testing parameters. |
|---------------------------------------------|
| Strain rate $\varepsilon$ ($s^{-1}$) | 0.001 | 0.01 | 0.1 | 0.5 |
| Temperature ($^\circ$C) | 575 | 600 | 625 | 650 |
Axisymmetric compression testing was done using Gleeble® 3500 thermo-mechanical equipment under the following conditions: temperatures of $575^\circ C$ to $650^\circ C$, a total strain of 0.7, and strain rates of $0.001$ to $0.5$ s$^{-1}$, as summarised in table 2. The warm deformation thermal profile is shown in figure 1.

3. Results and discussion

3.1. Stress-strain curves

The flow stress curves of the three P92 steels under strain rates of $0.001$ to $0.5$ s$^{-1}$ and a temperature range of $575^\circ C$ to $650^\circ C$ are shown in figures 3–5. The flow stress-strain curves exhibited an increase in the flow stress with an increase in strain up to a specific strain value before stress saturation occurred, as defined by Laasraoui and Jonas [23]. In the initial stages of deformation, the flow stress increased rapidly up to $\sim 0.3$ strain. This suggests that work hardening occurred due to an increase in dislocation density [24]. With further increase in strain above 0.3, the slope of the stress-strain curves decreased until the flow stress attained a steady state condition. This is due to a balance between work hardening and dynamic recovery (DRV) until saturation flow stress ($\sigma_{\text{sat}}$) occurs [23].

There was a decrease in flow stress with an increase in the deformation temperature for a given strain rate. This is due to an increase in diffusional mobility of atoms and an increase in dislocation mobility with temperature [24]. For a given temperature, the flow stress increased with an increase in the strain rate. These results are shown in table 3. For the three steels, DRV was the only softening mechanism, since the flow stress curves did not show the well-defined peak stress followed by the steady-state flow stress associated with dynamic recrystallization (DRX). Most of the flow stress curves exhibited a continuous increase in flow stress until a saturation stress ($\sigma_{\text{sat}}$) for DRV was reached, which could thus be measured directly from the stress-strain curves.
The flow stress curves of the three steels showed slightly different flow stress values for all the deformation conditions. Figure 6 shows the lowest and highest tested temperatures and strain rates. The P92-C steel had the highest flow stress values compared to P92-A and P92-B. One reason may be the higher chromium content in P92-C steel, as Cr enhances strengthening by forming precipitates that pin dislocations during deformation [6].

![Figure 4. Effect of temperature and strain rate on the stress-strain behaviour for P92-B steels.](image)

**Table 3.** Saturated flow stress obtained during warm deformation of P92 steels.

| Steel  | Strain rate (s⁻¹) | Saturation flow stress (σ_sat) in MPa at the tested temperatures (°C) |
|--------|------------------|---------------------------------------------------------------------|
|        |                  | 575  | 600  | 625  | 650  |
| P92-A  | 0.001            | 457  | 434  | 412  | 369  |
|        | 0.01             | 476  | 456  | 430  | 397  |
|        | 0.1              | 499  | 481  | 454  | 429  |
|        | 0.5              | 519  | 496  | 475  | 450  |
|        | 0.001            | 470  | 440  | 386  | 369  |
| P92-B  | 0.01             | 489  | 462  | 415  | 392  |
|        | 0.1              | 508  | 485  | 440  | 425  |
|        | 0.5              | 524  | 503  | 467  | 448  |
|        | 0.001            | 487  | 466  | 432  | 394  |
| P92-C  | 0.01             | 508  | 480  | 457  | 426  |
|        | 0.1              | 529  | 499  | 472  | 442  |
|        | 0.5              | 546  | 518  | 489  | 459  |
The saturation flow stress values determined from the experimental data for each steel at all the tested deformation conditions are given in Table 3.

3.2. Constitutive modelling

The hot working constitutive equation that characterises the flow stress in terms of deformation conditions was proposed by Sellars and Tegart [19]:

\[ \dot{\varepsilon} = A \left[ \sinh(\alpha \sigma) \right]^n \exp\left(\frac{-Q}{RT}\right) \]

where \( A, \alpha, \) and \( n \) are material constants, \( \sigma \) is the flow stress in MPa, \( Q \) is the deformation apparent activation energy, \( R \) is the universal gas constant and \( T \) is the absolute deformation temperature (K).

The hyperbolic sine equation is suitable for all flow stress. The peak stress and/or steady-state stress obtained from the flow stress curves are usually used to calculate the material constants [25]. However, the stress-strain curves in this work (Figures 3–5) did not exhibit a clear peak stress and steady-state stress after the peak. So, for this study, the material constants and activation energy were determined using the saturation flow stress, which occurs when an increase in the flow stress is limited by dynamic recovery, hence reaching a steady-state value. The saturation flow stress can be obtained directly from the stress-strain curve as shown by Laasraoui and Jonas [23] and Oudin et al [26]. Then equation (1) can be written as:

\[ \dot{\varepsilon} = A \left[ \sinh(\alpha \sigma_{sat}) \right]^n \exp\left(\frac{-Q}{RT}\right) \]  

The value of the stress multiplier \( \alpha \) is obtained by solving the power law (equation (4)) and exponential law (equation (5)) at constant temperature for low and high stresses respectively:
Figure 6. Comparison in flow stress for the three P92 steels under different deformation conditions.

Figure 7. P92-B steel. Plots of: (a) $\ln(\varepsilon)$ versus $\ln(\sigma)$ to determine $n'$, and (b) $\ln(\varepsilon)$ versus $\sigma$ to determine $\beta$. 
At low flow stress: 

\[ n' = \frac{\partial \ln \dot{\varepsilon}}{\partial \ln \sigma_{\text{sat}}} \]  

(4)

At high flow stress: 

\[ \beta = \frac{\partial \ln \dot{\varepsilon}}{\partial \sigma_{\text{sat}}} \]  

(5)

Then: 

\[ \alpha \approx \beta / n' \]  

(6)

where \( \beta \) and \( n' \) are material constants obtained from the slope of the curves using the power and exponential laws from equations (4) and (5) respectively.

Solving equation (2) and taking its partial derivative with \( \ln \dot{\varepsilon} \) at constant temperature:

\[ \frac{1}{n} = \frac{\partial \ln \left[ \sinh (\alpha \sigma_{\text{sat}}) \right]}{\partial \ln \dot{\varepsilon}} \]  

(7)

Similarly, at constant strain rate \( \dot{\varepsilon} \):

\[ Q = Rn \frac{\partial \ln \left[ \sinh (\alpha \sigma_{\text{sat}}) \right]}{\partial \frac{1}{T}} \]  

(8)

Qian et al [27] and Kishor et al [28] have pointed out that the Zener-Holloman parameter \( Z \) can be used to characterise the combined contribution of deformation temperature and strain rate on the resistance to
deformation. The relationship between the Zener-Holloman parameter and flow stress is given in equation (9) and is used to determine the value of $\ln A$ in equation (10) [29]:

$$Z = \dot{\varepsilon} \exp \left[ \frac{Q}{RT} \right] = f(\sigma) = A[\sinh(\alpha \sigma)]^n$$

Taking the natural logarithm of equation (6):

$$\ln Z = \ln A + n \ln \sinh(\alpha \sigma)$$

Figure 10. The relationship between $\ln Z$ and $\ln (\sinh(\alpha \sigma_{sat}))$ for the three P92 steels (a) P92-A (b) P92-B and (c) P92-C.

| Steel    | $n'$   | $\beta$ | $\alpha$ | $\sigma_{sat}$ | $Q$ (kJ mol$^{-1}$) | $\ln A$ |
|----------|--------|---------|----------|----------------|---------------------|---------|
| P92–A    | 42.2   | 0.093   | 0.00220  | 32.0           | 616                 | 75.5    |
| P92–B    | 41.6   | 0.091   | 0.00219  | 31.6           | 751                 | 89.2    |
| P92–C    | 51.4   | 0.108   | 0.00211  | 39.1           | 815                 | 100.7   |

Table 4. Calculated material constants and activation energy.

The material constants: $\alpha$, $\beta$, $n'$, $n$ and $Q$ were obtained by linear regression of equations (4)–(8) for the three steels as shown in figures 7–9, using the saturation flow stress values from table 2, and are summarised in table 4. The linear correlation coefficient between $\ln Z$ and $\ln \sinh(\alpha \sigma_{sat})$ were obtained as: 97.6% (P92–A), 96.9% (P92–B) and 98.8% (P92–C) from plots shown in figure 10.
Rewriting equation (3), the flow stress can be expressed in terms of the Zener-Hollomon parameter from equation (9):

$$\sigma_{sat} = \frac{1}{\alpha} \ln \left\{ \left( \frac{Z}{A} \right)^{1/n} + \left[ \left( \frac{Z}{A} \right)^{2/n} + 1 \right]^{1/2} \right\}$$

Using the saturated stress values from table 3 in the hyperbolic sine law (equation (2)), hot working constitutive equations were developed to predict the flow stress for the three P92 steels:

$$\text{P92} - A: \dot{\varepsilon} = 4.89 \times 10^{32} \sinh(0.00220 \sigma_{sat})^{32.0} \exp \left[ -\frac{616000}{RT} \right]$$

$$\text{P92} - B: \dot{\varepsilon} = 7.73 \times 10^{40} \sinh(0.00219 \sigma_{sat})^{31.6} \exp \left[ -\frac{751000}{RT} \right]$$

$$\text{P92} - C: \dot{\varepsilon} = 7.91 \times 10^{43} \sinh(0.00211 \sigma_{sat})^{39.1} \exp \left[ -\frac{815000}{RT} \right]$$

From equation (11), the saturation flow stress under different deformation conditions can be determined from the following equations for the three steels, given that, \( Z = \dot{\varepsilon} (Q/RT) \):

$$\text{P92} - A: \sigma_{sat} = \frac{1}{0.00220} \ln \left[ \left( \frac{Z}{4.89 \times 10^{32}} \right)^{32.0} + \left( \frac{Z}{4.89 \times 10^{32}} \right)^{2/32.0} \left[ 1 + \left( \frac{Z}{4.89 \times 10^{32}} \right)^{2/32.0} \right]^{0.5} \right]$$

$$\text{P92} - B: \sigma_{sat} = \frac{1}{0.00219} \ln \left[ \left( \frac{Z}{7.73 \times 10^{40}} \right)^{31.9} + \left( \frac{Z}{7.73 \times 10^{40}} \right)^{2/31.9} \left[ 1 + \left( \frac{Z}{7.73 \times 10^{40}} \right)^{2/31.9} \right]^{0.5} \right]$$

$$\text{P92} - C: \sigma_{sat} = \frac{1}{0.00211} \ln \left[ \left( \frac{Z}{7.91 \times 10^{43}} \right)^{39.1} + \left( \frac{Z}{7.91 \times 10^{43}} \right)^{2/39.1} \left[ 1 + \left( \frac{Z}{7.91 \times 10^{43}} \right)^{2/39.1} \right]^{0.5} \right]$$

### 3.3. Constitutive parameters

The stress exponent \( n \) range of 31.6–39.1 for the three P92 steels (table 4) is much higher than values reported in literature for hot deformation of P92 steel. Under deformation temperatures of 950 °C–1250 °C and strain rates of 0.01–10 s\(^{-1}\), \( n \) values of 4.76 [22] to 6.57 [12] have been determined. The tenfold difference in stress exponent can be attributed to the different deformation temperature range and strain rate range. Hot forming operations to produce P92 components, such as forged pipes, are typically done above 950 °C, and at strain rates above 10 s\(^{-1}\) [30]. P92 steel is then supplied for use as boiler pipes, headers and tubes in supercritical and ultra-supercritical power generation plants. These components are subjected to operating conditions up to ~620 °C and 25 MPa and low strain rates of 10\(^{-5}\) to 10\(^{-3}\) s\(^{-1}\), which are in the creep regime [21]. It has been shown that the stress exponent increases as the deformation temperature decreases under creep conditions. For example, Sawada, Kubo and Abe [31] showed that the stress exponent increased from 5.7 to 12.7 as the deformation temperature decreased from 750 to 650 °C. Since the compression tests in the present work were done in the lower temperature range of 575 °C–650 °C, within the operational range for the P92 steels, higher stress exponent values would be expected. These higher \( n \) values may be attributed to the interaction between the many evolved precipitates, such as the M\(_{23}\)C\(_6\) carbides and MX carbonitrides, with the mobile dislocations thus hindering the plastic deformation process [18]. Values of 15.1 to 28.8 have been reported for 9%–12% Cr steels under creep deformation conditions at 550 °C to 750 °C and low stress [18, 32–35]. Dissolution of precipitates increases with increasing temperature, so the volume fraction of precipitates increases as temperature decreases below the equilibrium dissolution temperature. For the three P92 steels in this work, the equilibrium dissolution temperatures of M\(_{23}\)C\(_6\) and MX precipitates determined using Thermo-Calc with the TCFe5 database [36] are listed in table 5.

There were differences in the apparent activation energy \( Q \) (table 4): 616 kJ mol\(^{-1}\) (P92-A), 751 kJ mol\(^{-1}\) (P92-B) and 815 kJ mol\(^{-1}\) (P92-C). The calculated material constants for P92-A and P92-B steels were the same. However, P92-B steel had higher activation energy than P92-A steel. This can be attributed to the higher flow stress values at lower deformation temperatures (575 °C–650 °C) as shown in figures 11(a) and (b), therefore the overall average value is higher than that of P92-A steel. P92-C steel had the highest activation energy due to high flow stress values in all the deformation conditions. Also, the differences in activation energy may be attributed to the effect of alloying elements as reported in the literature [15]. Minor alloying and impurity elements in steels, such as Mn, Ti, Si, Al and Nb, contribute to high Q values [13, 25, 37], as they decrease the diffusivity of Fe atoms in γ-iron and delay the occurrence of dynamic recrystallisation [8]. The presence of solute atoms...
contributes to solution strengthening by the formation of numerous precipitates that prevent dislocation movement during the deformation process, hence increasing the activation energy \[35, 38\]. Similarly, Suikkanen et al. \[39\] found that interstitial elements such as carbon and boron reduce activation energy, since they enhance diffusion while substitutional elements increase \(Q\). Therefore, as the amount of substitutional alloying elements increases, the activation energy increases \[39\], due to an accumulation of internally stored energy \[40\].

The calculated activation energy indicates the deformation resistance under a specific set of deformation conditions \[41\]. The mean \(Q\) values were much higher than the 270 kJ mol\(^{-1}\) for self-diffusion of iron in austenite \[42\] and 250 kJ mol\(^{-1}\) for iron in ferrite \[38\]. The calculated activation energy of 616 kJ mol\(^{-1}\) for P92-A steel is in the same range as 628 kJ mol\(^{-1}\) for a P92 steel \[43\]. The other two steels in the current study had

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**Figure 11.** (a) and (b) Dependence of saturated flow stress on the strain rate at two temperatures. (c) Effect of the calculated equilibrium amount of M23C6 on the activation energy.

**Table 5.** Thermo-Calc equilibrium dissolution temperatures of M23C6 and MX precipitates.

| Steel  | M23C6 (°C) | MX (°C) |
|--------|------------|---------|
| P92–A  | 870        | 1201    |
| P92–B  | 888        | 1250    |
| P92–C  | 911        | 1192    |
higher activation energies, indicating that deformation was more difficult. Anderson et al.[34] found that a modified 9Cr-1Mo steel had a higher activation energy of 786 kJ mol⁻¹ under creep conditions at 550–650 °C. They further reported that, when creep deformation was done at lower temperatures (550 °C) and high stresses (>100 MPa), the n was 22 and the Q was very high at 1117 kJ mol⁻¹. In contrast, at a higher temperature of 650 °C and a low stress of 100 MPa, the values decreased markedly to an n of 3.9 and Q of 216 kJ mol⁻¹. This shows that the high material constant and activation energy values of the P92 steels in the current study fit into the creep temperature range, but at higher strain rates than experienced during creep deformation. In general, the three steels exhibited higher resistance to uniaxial compression than other 9%–12% Cr steels reported in the literature[25]. Moreover, the higher activation energy can also be due to the high values of the stress exponent.

At a given temperature and strain rate, P92-C had the highest flow stress as shown in figures 11(a) and (b). The variations in flow stress of the three steels could possibly be attributed to the amount of M23C6 precipitates. The theoretical content of these precipitates in the testing temperature range was determined by Thermo-Calc and is shown in figure 11(c). As the volume fraction of the M23C6 precipitates increased the activation energy increased, showing that these precipitates contributed to the activation energy. This shows that the activation energy was affected by the deformation parameters, the microstructure evolution during the deformation process, and therefore also the chemical composition.

### 3.4. Statistical error analysis

The applicability of the developed constitutive equations for prediction of flow stress was analysed using the standard statistical parameters such as the Pearson’s correlation coefficient R and the average absolute relative error AARE as given in equations (18) and (19) respectively. These parameters have been widely used to show the capability of the developed model to predict flow stress[15, 27, 44]:

**Figure 12.** Comparison between predicted and experimental flow stress of the three P92 steels for all deformation conditions (a) P92-A (b) P92-B and (c) P92-C.
\[
R = \frac{\sum_{i=1}^{N}(E_i - \bar{E})(P_i - \bar{P})}{\sqrt{\sum_{i=1}^{N}(E_i - \bar{E})^2 \sum_{i=1}^{N}(P_i - \bar{P})^2}}
\]  
(18)

\[
\text{AARE}(\%) = \frac{1}{N} \sum_{i=1}^{N} \left[ \frac{E_i - P_i}{E_i} \right]
\]  
(19)

where \( E \) is the experimental flow stress, \( P \) is the predicted flow stress and \( \bar{E} \) and \( \bar{P} \) are their average values. \( N \) is the total population of data points used in the analysis.

From the scatter map of the experimental and predicted flow stresses (figure 12) for all the deformation conditions, the Pearson’s correlation coefficients for the tested steels are high at approximately 0.987 (P92-A), 0.997 (P92-B) and 0.990 (P92-C), where 1.00 indicates perfect correlation. However, a good correlation between the two variables does not necessarily depend on the value of Pearson’s correlation coefficient since the predicting constitutive model might be biased towards the extreme values \(^{45}\). Therefore, AARE analysis gives the accuracy of the developed constitutive model since the relative error for each flow stress term is determined. The percentage relative error was determined as 1.1% (P92-A), 0.8% (P92-B) and 0.9% (P92-C). This shows that the developed constitutive equations have sufficient statistical integrity to predict the flow stress for the three steels tested under the specific warm deformation conditions.

4. Conclusions

1. The friction corrected flow stress-curves obtained from the experimental data showed that the flow stress decreased with an increase in the deformation temperature from 575 °C to 650 °C and with a decrease in the strain rate from 0.5 to 0.001 s\(^{-1}\).

2. At lower strains (\( \varepsilon < 0.3 \)), the steels exhibited work hardening. However, at high strains (\( \varepsilon > 0.3 \)), the slope of the flow stress curves decreased due to the interaction between the work hardening and softening mechanisms, resulting in a saturation flow stress. At this stage, dynamic recovery was the dominant softening mechanism.

3. The constitutive constants of the three P92 steels were calculated for compression testing at 575 °C–650 °C and 0.001–0.5 s\(^{-1}\). The strain hardening coefficients (\( n \)) were 32.0 (P92-A), 31.6 (P92-B) and 39.1 (P92-C). The warm deformation activation energy values for the three steels were 616 kJ mol\(^{-1}\) (P92-A), 751 kJ mol\(^{-1}\) (P92-B) and 815 kJ mol\(^{-1}\) (P92-C). These differences in the activation energy may be due to changes in the chemical composition influencing the amount of precipitates, where an increase in the amount of precipitates would increase the activation energy.

4. The validity of the developed constitutive model was analysed statistically using Pearson’s correlation coefficient (R) and the absolute average relative error (AARE). There was good correlation between the predicted and the experimental data.

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References

[1] Tabuchi M, Watanabe T, Kubo K, Matsui M, Kinugawa J and Abe F 2001 Creep crack growth behavior in the HAZ of weldments of W containing high Cr steel Int. J. Press. Vessel. Pip. 78 779–84

[2] Nagode A, Kosec L, Ule B and Kosec G 2011 Review of creep resistant alloys for power plant applications Metalurgija 50 45–8

[3] Oñoro J 2006 Weld metal microstructure analysis of 9–12% Cr steels Int. J. Press. Vessel. Pip. 83 540–5

[4] David S A, Siefert J A and Feng Z 2013 Welding and weldability of candidate ferritic alloys for future advanced ultrsupercritical fossil power plants Sci. Technol. Weld. Join. 18 631–51

[5] Milović I, Vuherer T, Ilačić I, Vrhovac M and Stanković M 2013 Microstructures and mechanical properties of creep resistant steel for application at elevated temperatures Mater. Des. 46 660–7

[6] Czyrska-filemonowicz A, Ziel choixka-lipiec A and Ennis P J 2006 Modified 9% Cr steels for advanced power generation: microstructure and properties J. Achiev. Mater. Manuf. Eng. 19 43–8
[7] Saktihivel T et al 2014 Creep rupture behavior of 9Cr-1.8W–0.5Mo–VNb (ASME grade 92) ferritic steel weld joint Mater. Sci. Eng. A 591 111–20
[8] Carst M, Peñalba F, Rieiro I and Ruano O A 2011 High temperature workability behavior of a modified P92 steel Int. J. Mater. Res. 102 1376–83
[9] Saini N, Pandey C and Mahapatra M M 2017 Characterization and evaluation of mechanical properties of CSEF P92 steel for varying normalizing temperature Mater. Sci. Eng. A 688 250–61
[10] Wang X, Xu Q, Yu S M, Hu L, Liu H and Ren F Y 2015 Laves-phase evolution during aging in 9Cr–1.8W–0.5Mo–VNb steel for USC power plants Mater. Chem. Phys. 163 219–28
[11] Medina S F and Hernandez C A 1996 General expression of the Zener-Hollomon parameter as a function of the chemical composition of low alloy and microalloyed steels Acta Mater. 44 137–44
[12] Shi R X and Liu Z D 2011 Hot deformation behavior of P92 steel used for ultra-super-critical power plants J. Iron. Steel. Res. Int. 18 53–8
[13] Menapace C, Sartori N, Pellizzari M and Straffolini G 2018 Hot deformation behavior of four steels: a comparative study J. Eng. Mater. Technol. 140 021006
[14] Vasilyev A A and Golikov P A 2018 Carbon diffusion coefficient in alloyed ferrite Mater. Phys. Mech. 39 111–9
[15] Yang Z N, Dai L Q, Chu C H, Zhang F C, Wang L W and Xiao A P 2017 Effect of aluminum alloying on the hot deformation behavior of nano-bainitic bearing steel J. Mater. Eng. Perform. 26 5954–62
[16] Vasilyev A A, Sokolov S F, Kolbasnikov N G and Sokolov D F 2011 Effect of alloying on the self-diffusion activation energy in γ-iron Phys. Solid State 53 2194–200
[17] Wang L, Liu F, Cheng J J, Zuo Q and Chen C F 2015 Hot deformation characteristics and processing map analysis for Nickel-based corrosion resistant alloy J. Alloys Compd. 623 69–78
[18] Emnis P J, Zielinska-Liepic A, Wachter O and Czyrski-Filemonowicz A 1997 Microstructural stability and creep rupture strength of the martensitic steel P92 for advanced power plant Acta Mater. 45 4901–7
[19] Sellers C M and McTegart W J 1966 On the mechanism of hot deformation Acta Metall. 14 1136–8
[20] Samantaray D, Mandal S and Bhaduri A K 2010 Constitutive analysis to predict high-temperature flow stress in modified 9Cr–1Mo (P91) steel J. Mater. Process. Technol. 31 981–4
[21] Sun S L, Zhang M G and He W W 2010 Hot deformation behavior and hot processing map of P92 steel Adv. Mater. Res. 97–101 290–5
[22] Liu C Y, Zhang R J and Yan Y N 2011 Hot deformation behaviour and constitutive modelling of P92 heat resistant steel Mater. Sci. Technol. 27 1281–6
[23] Laasraoui A and Jonas J J 1991 Prediction of steel flow stresses at high temperatures and strain rates Metall. Trans. A 22 1545–58
[24] Zhu L, He J and Zhang Y 2018 A two-stage constitutive model of X12CrMoVWNbN10-1-1 steel during elevated temperature Mater. Res. Express 5 026505
[25] McQueen H J and Ryan N D 2002 Constitutive analysis in hot working Mater. Sci. Eng. A 322 43–63
[26] Oudin A, Barnett M R and Hodgson P D 2004 Grain size effect on the warm deformation behaviour of a Ti-IF steel Mater. Sci. Eng. A 367 282–94
[27] Qian L Y, Fang G, Zeng P and Wang L X 2015 Correction of flow stress and determination of constitutive constants for hot working of API X100 pipeline steel Int. J. Press. Vessel. Pip. 132–133 43–51
[28] Kishor B, Chaudhari G P and Nath S K 2016 Hot deformation characteristics of 13Cr–4Ni stainless steel using constitutive equation and processing map J. Mater. Eng. Perform. 25 2651–60
[29] Mirzaee H 2015 A simplified approach for developing constitutive equations for modeling and prediction of hot deformation flow stress Metall. Mater. Trans. A 46 4027–37
[30] Osakada K 2007 Effects of strain rate and temperature in forming processes of metals Int. J. Mech. Sci. 49 1337–47
[31] Sawada K, Kubo K and Abe F 2001 Creep behavior and stability of MX precipitates at high temperature in 9Cr–0.5Mo–1.8W–VNb steel Mater. Sci. Eng. A 319 784–7
[32] Fedoseeva A, Dudnova N and Kaibyshev R 2016 Creep strength breakdown and microstructure evolution in a 3%Co modified P92 steel Materials Science and Engineering A 654 1–12
[33] Saktihivel T, Selvi S P, Parameswaran P and Laha K 2016 Creep deformation and rupture behaviour of thermal aged P92 steel Mater. High Temp. 33 33–43
[34] Anderson P, Bellgaard T and Jones F L 2003 Creep deformation in a modified 9Cr–1 Mo steel material Mater. Sci. Technol. 19 207–13
[35] Zhang X Z, Wu X J, Liu R, Liu J and Yao M X 2017 Deformation-mechanism-based modeling of creep behavior of modified 9Cr–1Mo steel Mater. Sci. Eng. A 689 345–52
[36] Software T, Andersson J-O, Helander T, Hedghmd L, Shi P and Sundman B 2002 THERMO-CALC & DICTRA, computational tools for materials science Calphad Comput. Coupling Phase Diagrams Thermochem. 26 273–312
[37] Fedoseeva A, Dudnova N and Kaibyshev R 2016 Creep strength breakdown and microstructure evolution in a 3%Co modified P92 steel Mater. Sci. Eng. A vol. 654 1–12
[38] Ashley M F 1972 A first report on deformation-mechanism maps Acta Metall. 20 887–97
[39] Suikkanen P P, Lang V T E, Somari M C, Porter D A and Karjalainen J P 2012 Effect of Silicon and Aluminium on Austenite Static Recrystallization Kinetics in High-strength TRIP-aided Steels ISIJ Int. 52 471–47
[40] Zhang J, Di H, Wang X, Cao Y, Zhang J and Ma T 2013 Constitutive analysis of the hot deformation behavior of Fe-23Mn-2Al-0.2C twinning induced plasticity steel in consideration of strain Mater. Des. 44 354–64
[41] Yang Z, Zhang F, Zheng C, Zhang M, Lv B and Qu L 2015 Study on hot deformation behaviour and processing maps of low carbon bainitic steel Mater. Des. 66 258–66
[42] Cabrera M, Al-Omar A, Jonas J I and Prado J M 1997 Modeling the flow behavior of a medium carbon microalloyed steel under hot working conditions Metall. Trans. A Phys. Metall. Mater. Sci. 28 2323–33
[43] Asagabashi S 2016 High Temperature deformation behavior of P92 steel Trans. Indian Inst. Met. 69 1513–8
[44] He A, Xie G, Zhang H and Wang X 2013 A comparative study on Johnson-Cook, modified Johnson-Cook and Arhenius-type constitutive models to predict the high temperature flow stress in 20CrMo alloy steel Mater. Des. 52 677–85
[45] He A, Xie G, Yang X, Wang X and Zhang H 2015 A physically-based constitutive model for a nitrogen alloyed ultralow carbon stainless steel Comput. Mater. Sci. 98 64–9