Materials Research Express

OPEN ACCESS

PAPER

Modelling approach for predicting the superplastic deformation behaviour of titanium alloys with strain hardening/softening characterizations

A O Mosleh1,2,4, P Mestre-Rinn1, A M Khalil1,2, A D Kotov1 and A V Mikhaylovskaya1

1 National University of Science and Technology ‘MISiS’, Leninsky Prospekt, 4, Moscow 119049, Russia
2 Shoubra Faculty of Engineering, Benha University, Shoubra St. 108, Shoubra, P O 11629, Cairo, Egypt
3 Ecole Nationale Supérieure des Mines de Saint-Etienne,158 Cours Fauriel, 42100 Saint-Etienne, France
4 Author to whom any correspondence should be addressed.

E-mail: mosleh@misis.ru and ahmed.omar@feng.bu.edu.eg

Keywords: tensile testing, titanium alloys, mathematical modelling, flow behaviour, constitutive equations, superplastic deformation

Abstract

This paper introduces an approach for modelling the flow behaviour of different titanium alloys (VT6, OT4-1 and VT14 alloys by Russian specifications) in superplastic deformation temperature and strain rate ranges. The initial microstructure parameters \(d_{\alpha,\beta}, V_{\alpha,\beta}\) before starting the deformation test were included in the constructed model for each alloy. The investigated alloys have different initial microstructures and flow behaviour characteristics. The isothermal uniaxial tensile deformation tests were performed at the superplastic deformation temperature and strain rate ranges of each alloy. The VT6, OT4-1 alloys were characterized by strain hardening effect during the deformation test, while VT14 alloy was characterized by strain softening effect. A comparison study between the experimental and modelled data was performed. The general equation of the constructed models was affected by the chilling microstructure and flow behaviour characteristics. The correlation coefficient \(R\) was 0.98, 0.95 and 0.97 for VT6, OT4-1 and VT14, respectively. The predictability of the constructed model was assessed by the cross-validation technique, which ascertained the quality of the constructed model.

1. Introduction

Titanium and its alloys are found in many applications, especially in the aerospace, because of their natural mechanical and physical properties as well as corrosion durability [1–3]. The properties of the Ti-based alloys make it a difficult material to deform at room temperature, with high dependence on parameters like the forming temperature or the strain rate [4]. Superplastic forming (SPF) appears to be a good solution, giving the possibility to reduce the necessary flow stress deformation at high temperature [5–9]. The superplasticity is defined as the ability of a polycrystalline material to display a large elongation prior to failure due to high strain rate sensitivity of the flow stress. Metallic alloys are considered to be superplastic alloys when the obtained tensile elongation, without necking, more than 200%–400% [10]. Deformation temperature higher than 0.5 of the solidus/transus temperature and grain size finer than 10 \(\mu\)m are the main requirements to achieve the superplastic forming process [11, 12].

There are many parameters affect the flow behaviour at high temperature; (1) parameters related to the deformation process such as the deformation temperatures and strain rates [10, 13]. (2) parameters related to the microstructure of investigated alloy such as alloy chemistry, grain growth kinetics, grain size distribution, grain aspect ratio, volume fraction of phases and texture [14–20]. The influence of the both deformation temperature and strain rate on the elongation to failure and strain-hardening coefficient of the VT6, OT4-1 and VT14 alloys was studied in [10]. The most influential parameter was the temperature of the VT14 and OT4-1 alloys and the strain rate of the VT6 alloy. Generally, low deformation temperature is preferred for energy consumption,
shorter forming cycle times, reduced oxidation, increased die life and lower die cost [21]. Decreasing the deformation temperature is achieved by decreasing the initial grain size [22]. Early research of superplasticity indicated the requirement of a two-phase microstructure with approximately equal fraction of phases to provide comparable deformation characteristics. A large number of interphase boundaries is advisable for retarding grain growth during the deformation process [4].

As the flow stresses are the main exit, their analyse help to understand the behaviour of the structure during the forming process, and so to identify the best conditions for forming. Different microstructures need different forming conditions, usually fixed by optimizing the deformation temperature and strain rate, in order to reduce the flow stress and maximize the elongation. Knowledge about the flow behaviour is necessary to optimise the conditions of superplastic deformation, as it depends on so many factors [10, 23–36]. Modelling of the flow behaviour at tensile tests is conducted to find the relation of stress versus temperature and strain-rate. These models use in finite element simulation and help to optimize the superplastic forming process of complex shape parts. The treatments regimes and slight variations of a chemical composition significantly influence to the microstructural parameters. As far as a flow stress value and a flow behaviour strongly affected by microstructure, it is very important to implement the microstructural parameters in the models of the deformation behaviour. It helps to decrease the amount of high temperature tests, save the material and cost of the superplastic forming process and increased quality of the formed parts. The aim of this paper is to introduce an approach for flow behaviour modelling of different titanium alloys in a range of temperature and strain rate of the superplastic deformation. The annealing process was utilized to indicate the microstructure parameters before starting the uniaxial tensile tests. These parameters were used to demonstrate the superplastic temperature ranges of the investigated alloys. The obtained flow behaviour, which characterized by strain hardening or softening effect, was modelled using empirically developed models.

2. Materials and test experiments

Ti-based alloys with different initial microstructures, Ti+6%Al+4%V, Ti+2.5%Al+1.8%Mn and Ti+4%Al +3%Mö+1%V (VT6 (α+β), OT4-1 (Near-α) and VT14 (α+β) by Russian specifications), were investigated. The thicknesses of the as-received flat sheets were 1, 1.55 and 1.22 mm for VT6, OT4-1 and VT14, respectively. The initial samples were annealed for 30 min in a temperature range of (α + β) region of each alloy, then were water quenched in order to analyse the microstructure and to obtain the microstructure parameters at the testing temperatures. The annealing process was performed under a protective argon atmosphere to prevent the oxidation. For microstructure analysis, the polishing was achieved via a Struers LaboPol-5 automatic machine. The polishing steps comprised papers up to 2400 grit then micro cloths (CHEM MD) with a lubricant of 50 ml colloidal silica (0.02 μm) + 10 ml H₂O₂ (30%) + 5 ml Kroll’s agent until the surface became mirror-like. The dog-bone flat samples according to ASTM E2448-18 standard were cut in the rolling direction, then tested via a Walter–Bay LFM100 test machine (Walter + Bai AG, Löhnningen, Switzerland). The superplastic strain rate for each alloy were determined in [19, 37, 38]. The stress-strain data of each alloy were utilized to build up the proposed models.

3. Results and discussions

3.1. Determination of the microstructure parameters

The microstructure parameters were determined after 30 min annealing at the investigated temperatures before starting of the deformation test. Figure 1 shows the initial two-phase structure of α (dark) and β (bright) after 30 min annealing for the investigated alloys, VT6 (figures 1(a)–(c)), OT4-1 ((figures 1(d)–(f)) and VT14 alloys (figures 1(g)–(i)). The initial microstructure VT14 alloy exhibited a mixture structure (equiaxed and non-recrystallized structure) (figure 1(g)). Generally, increasing the deformation temperature led to increase the both α and β grains size and increase the volume fraction of β-phase. Figure 2 shows the quantitative analysis of the microstructural parameters (Iα,β and Vα,β) at different annealing temperature for each alloy. The volume fraction of β-phase was close to 50% at different temperature range for each alloy. It was 875 °C–900 °C, 875 °C–900 °C and 875 °C–900 °C for VT6 alloy (figure 2(a)), OT4-1 alloy (figure 2(b)) and VT14 alloy (figure 2(c)), respectively. The grain growth rate for β-grains was larger than the grain growth rate of α-grains in case of VT6 (figure 2(a)) and VT14 alloys (figure 2(c)), but in case of OT4-1 alloy, the grain growth of both β and α-grains nearly the same (figure 2(b)).

3.2. Uniaxial tensile tests results

Figure 3 shows the flow stress-strain dependence of the investigated alloys. In a studied temperature-strain rate range, the alloys have a strain rate sensitivity index-\(m\) in a range of 0.41–0.59 that provided highly uniform
necking free superplastic deformation. The both VT6 (figures 3(a)–(c)) and OT4-1 (figures 3(d)–(f)) alloys are characterized predominantly by a strain hardening, while the VT14 alloy (figures 3(g)–(h)) is mostly characterized by a strain softening. A similar characterization was noted for VT6 and OT4-1 alloys in [37, 39, 40], and for VT14 alloy in [19, 41].

A flow behaviour of the investigated alloys depends on microstructure evolution during the deformation process. The strain hardening is possible due to dynamic grain growth, and the strain softening can be a result of dynamic recrystallization effect. Figure 4 shows the microstructure of the VT6 (figures 4(a)–(c)), OT4-1 (figures 4(d)–(f)) and VT14 (figures 4(g)–(i)) alloys at the optimum deformation condition of each alloy after various strains.

The both VT6 and OT4-1 alloys exhibited globular (recrystallized) structure before start of the deformation process, $e = 0$ (figures 4(a), (d)). At a strain of $0.4 \rightarrow 1.1$, the dynamic grain growth of both $\alpha$ and $\beta$ grains was observed in VT6 (figures 4(b), (c)) and OT4-1 (figures 4(e), (f)) alloys. Thus, the dynamic grain growth was
considered as a main reason of the hardening effect of these alloys. Strain hardening effect increases with decreasing strain rate and increasing temperature (figures 3(a)–(f)) and it can be explained by more intensive grain growth.

Before start of the deformation, VT14 alloy exhibited a mixture structure that consisted of lamellar (non-recrystallized) and globular (recrystallized) parts (figure 4(g)). Superplastic deformation led to transformation the elongated lamellar areas to the equiaxed grains (figure 4(h)) that is possible due to dynamic recrystallization. After strain of 1.1, an equiaxed grain structure was formed in VT14 alloy (figure 4(i)). Dynamic recrystallization is considered as a main reason of the softening effect in the alloy. The strain softening intensified with increasing strain rate and decreasing temperature (figures 3(g)–(i)). Thus, this behaviour can be explained by competition between dynamic recrystallization and dynamic grain growth. It is notable that a dynamic grain growth was less pronounced in VT14 comparing to the other alloys, but its' grains were also grown at deformation [19, 41].

Firstly, dynamic recrystallization kinetics raises and the phenomenon required less time/strains with increasing temperature and decreasing strain rate. Secondary, the grain growth intensifies at high temperature deformation and it may be a reason of higher stress values that can compensate the softening effect at low strain rates and high temperature deformation.

3.3. Mathematical modelling with consideration of microstructure parameters

An empirical mathematical model is constructed for predicting the flow behaviour of the investigated alloys. The flow stress depends on deformation temperature, strain rate, strain and microstructure parameters equation (1).

\[
\sigma = f (\varepsilon, \varepsilon', T, d_{\alpha,\beta}, V_{\alpha,\beta})
\]

where,
- \(\sigma\), \(\varepsilon\), \(\varepsilon'\), \(T\) are the flow stress, strain, strain rate, and temperature, respectively.
- \(d_{\alpha,\beta}\), \(V_{\alpha,\beta}\) are the microstructure parameters, for ease of reference, the all microstructure parameters were included as one parameter \(D_0 = f (d_{\alpha,\beta}, V_{\alpha,\beta})\). The \(D_0\) is depending on the characterization of the flow behaviour of each alloy, strain hardening or strain softening effect.

![Figure 3. Dependence of stress on strain at several temperatures and strain rates for the investigated alloys: (a)–(c) VT6 alloy, (d)–(f) OT4-1 alloy, and (g)–(i) VT14 alloy.](image-url)
The equation (1) can write as following equation (2).

$$\sigma = K(t) \times D_0 \times \varepsilon^n \times \left( \frac{\varepsilon}{\varepsilon_0} \right)^{m_0} \times \left( \frac{T}{T_0} \right)^{q}$$  \hspace{1cm} (2)

$K(t) \times D_0 \times \varepsilon^n \rightarrow$ is the strain hardening impact

$\left( \frac{\varepsilon}{\varepsilon_0} \right)^{m_0} \rightarrow$ is the strain rate hardening impact

$\left( \frac{T}{T_0} \right)^{q} \rightarrow$ is the thermal softening impact

$K(t)$ is the equation constant. $\varepsilon_0$ and $T_0$ are the references strain rate and temperature, respectively.

The selected reference strain rate and temperature for each alloy are presented in table 1. As in Johnson-cook model generally, the minimum experimental temperature is selected to be a reference temperature in such a way that $T \geq T_{ref}$ according to [42–45]. By the same way, the minimum experimental strain rate and temperature were considered as references strain rate and temperature for each alloy in this study.

| Alloy   | $\varepsilon_0$ [s$^{-1}$] | $T_0$ [°C] |
|---------|---------------------------|------------|
| VT6     | $5 \times 10^{-4}$        | 800        |
| OT4-1   | $2 \times 10^{-4}$        | 840        |
| VT14    | $2 \times 10^{-4}$        | 800        |

Table 1. The used reference strain rate and temperature for each alloy.
3.3.1 Model constants determination

The VT6 alloy is used to be a guide example for determine the constants of the alloys which are characterized by strain hardening effect. In case of VT14 alloy, which characterized by strain softening effect, the $D_0$ equation was different.

3.3.1.1 Determination of $K(t)$, $D_0$ and $n$

At reference strain rate and temperature of VT6 alloy, $3 \times 10^{-4}$ s$^{-1}$ and 800 $^\circ$C, the equation (2) can be written as follows (equations (3) and (4));

\[
\sigma = K(t) \times D_0 \times e^n
\]

(3)

\[
\ln(\sigma) = \ln(K(t) \times D_0) + n \ln(e)
\]

(4)

where $D_0(T) = \frac{d_0}{d_{\text{cl,cl}}_{\text{c}}}$ (dimension less parameter) and is related to temperature, $K(t)$ is the shift factor and related to temperature.

Figure 5 shows the linear plots of $\ln(e) - \ln(\sigma)$ (figure 5(a)) and the dependence of the microstructure parameter ($D_0$) on the temperature (figure 5(b)) for VT6 alloy. The values of the line slope and the intersection from $\ln(e) - \ln(\sigma)$ curve are used to compute the ($K(t) \times D_0$) and $n$.

Therefore, the $n$ value is $= 0.25$. The $D_0(T)$ and $k(t)$ are computed from equations (5) and (6).

\[
D_0(T) = 19.6 + 670.4 \times \exp(-0.0024 \times T[^\circ\text{C}])
\]

(5)

\[
K(t) = -0.3 + 9.53 \times T[^\circ\text{C}]
\]

(6)

3.3.1.2 Determination of $m$

At 800 $^\circ$C, reference temperature of VT6 alloy, the equation (2) can be written as follows (equations (7) and (8));

\[
\sigma = K(t) \times D_0 \times e^n \times \left(\frac{\varepsilon'}{\varepsilon_0}\right)^{m_0} \rightarrow \frac{\sigma}{K(t) \times D_0 \times e^n} = \left(\frac{\varepsilon'}{\varepsilon_0}\right)^{m_0}
\]

(7)

\[
\ln\left(\frac{\sigma}{K(t) \times D_0 \times e^n}\right) = m_0 \times \ln\left(\frac{\varepsilon'}{\varepsilon_0}\right)
\]

(8)

Based on equation (7), the $m_0$ values can be determined from the slope of the fitted lines in $\frac{\sigma}{K(t) \times D_0 \times e^n}$ versus $\ln\left(\frac{\varepsilon'}{\varepsilon_0}\right)$ curve, figure 6(a). Figure 6(b) shows the $m_0$ values versus strain. The $m_0$ values are fitted by equation (9).

\[
m_0 = -0.02 + 0.66 \times \exp(-1.07 \times e)
\]

(9)

3.3.1.3 Determination of $\theta$

At $3 \times 10^{-4}$ s$^{-1}$, the reference strain rate of VT6 alloy, the thermal softening impact on the flow stress should be isolated. Thus, equation (2) can be defined as equations (10) and (11).
The dependence of $\ln K_t D_e n_0 s$ versus $\ln T_0$ is illustrated in figure 7(a). The $\theta$ values are determined from the slope of the regressed lines at several strains, then the $\theta$ versus strain data were regressed by equation (12) (figure 7(b)).

\[
\theta = -3.025 - 7.22 \times \exp(-1.73 \times e)
\]

Therefore, the constructed model for VT6 can be described by equation (13).

\[
\begin{align*}
\sigma &= K(t) \times D_0 \times e^{n_0} \times \left( \frac{T}{T_0} \right)^\theta \\
D_0(T) &= 19.6 + 670.4 \times \exp(-0.0024 \times T[\text{°C}]) \\
K(t) &= -0.3 + 9.53 \times T[\text{°C}] \\
n_0 &= -0.02 + 0.66 \times \exp(-1.07 \times e) \\
\theta &= -3.025 - 7.22 \times \exp(-1.73 \times e)
\end{align*}
\]
3.4. Model verification

Figure 8 shows the comparison between the experimental and predicted data obtained by the constructed model of VT6 alloy (figures 8(a)–(e)) and the correlation between experimental and fitted flow stress (figure 8(f)). The quality of the constructed model was appraised by using standard statistical quantities equations (14)–(16). The values of R, AARE and RMSE for this alloy were 0.975, 5.7% and 2.8 MPa, respectively.

\[
\text{correlation coefficient (R)} = \frac{\sum_{i=1}^{N} (E_i - E')(P_i - P')}{\sqrt{\sum_{i=1}^{N} (E_i - E')^2 \sum_{i=1}^{N} (P_i - P')^2}}
\]  
\[
\text{average absolute relative error (AARE)} = \frac{1}{N} \sum_{i=1}^{N} \left| \frac{E_i - P_i}{E_i} \right|
\]  
\[
\text{root mean square error (RMSE)} = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (E_i - P_i)^2}
\]

Figure 8 and the standard statistical quantities values prove the excellent predictability of the constructed model for VT6 titanium alloy. This model exhibits a good performance, efficiency compared with the constructed model for the same alloy by Mosleh et al [38].

By the same sequences, the model for prediction the flow behaviour of OT4-1 alloy can be illustrated. Figure 9 shows the plots for determining the model constants of OT4-1 alloy. The intersection and the slope of \(\ln(\sigma) - \ln(e)\) curve (figure 9(a)) were used to determine the \(K(t), D_0\) and \(n\) (figure 9(b)). The average of the slopes of lines in figure 9(c) was used to determine the \(m_0\) values (figure 9(d)). The average of the slopes of lines in figure 9(e) was utilized for determining the \(\theta\) values (figure 9(f)). Thus, the constructed model for predicting the flow behaviour of OT4-1 alloy can be summarized as follows (equation (17)).

\[
\begin{align*}
\sigma &= K(t) \times D_0 \times e^{0.3} \times \left( \frac{\Delta t}{\Delta t_0} \right)^m \times \left( \frac{T}{T_0} \right)^\theta \\
D_0(T) &= \frac{d_\beta V_n + d_\alpha V_n}{\sqrt{d_\alpha d_\beta}} = 57.9 + 0.0012 \times \exp(0.012 \times T[{^\circ}C]) \\
K(t) &= 0.3463 - 1.508 \times \exp(0.008 \times T[{^\circ}C]) \\
m_0 &= 0.088 + 0.563 \times \exp(-1.9 \times e) \\
\theta &= -1.94 - 6.8 \times \exp(-1.5 \times e)
\end{align*}
\]

The predictability of the constructed model was assessed using the same standard statistical quantities which stated in equations (14)–(16). The values of R, AARE and RMSE for this alloy were 0.95, 5.2% and 1.1 MPa.
respectively. These statistical values are closed to those obtained in [46] for the same alloy and Arrhenius-type constitutive or Artificial neural network models.

Figure 10 shows the comparison between the experimental and predicted data of the model (equation (17)) (figures 10(a)–(d)) and the correlation between experimental and fitted flow stress (figure 10(e)) for OT4-1 alloy. The predicted values are in a good agreement with the experimental data, which proves the capability of the constructed model to predict the flow behaviour of OT4-1 alloy.

By the same way, the model for predicting the flow behaviour of VT14 alloy, which characterized by strain softening was constructed. The equation (2) was written as follows equation (18).

\[
\sigma = K(t) \times D_0 \times f(\varepsilon) \times \left(\frac{\varepsilon}{\varepsilon_0^m}\right)^n \times \left(\frac{T}{T_0}\right)^\theta
\] (18)

The dependence of the flow stress on the strain \(\sigma = K(t) \times D_0 \times f(\varepsilon)\) at reference temperature and strain rate of this alloy is illustrated in figure 11(a). The dependence of \(D_0\) on the temperature is shown in figure 11(b). The average of the slopes of lines in figure 11(c) was used to determine the \(m_0\) values (figure 11(d)). The average of the slopes of lines in figure 11(e) was utilized for determining the \(\theta\) values (figure 11(f)). Thus, the constructed model for predicting the flow behaviour of VT14 alloy can summarized as follows (equation (17)).
Figure 10. Comparative plots for the experimental results (lines) and fitted values of constructed model (symbols) of OT4-1 alloy at (a) 840 °C, (b) 852 °C, (c) 865 °C, (d) 890 °C and (e) the correlation between experimental and fitted flow stress.

Figure 11. (a) Dependence of flow stress on strain at reference temperature-strain rate regime for VT14 alloy, (b) microstructure parameter ($D_0$) versus temperature, (c) relationship between $\frac{\sigma}{T(0)} = D_0 e^{\theta}$ and $\ln \left( \frac{\sigma}{T(0)} \right)$ for strains of 0.1 to 1, (d) dependence of $m_0$ versus strain, (e) relationship between $\ln \left( \frac{\sigma}{T(0)} = D_0 e^{\theta} \right)$ and $\ln \left( \frac{\sigma}{T_0} \right)$ for strain from 0.1 to 1 and (f) dependence of $\theta$ versus strain.
The predictability of the constructed model was assessed using the same standard statistical quantities which stated in equations (14)–(16). The values of R, AARE and RMSE for this alloy were 0.97, 7.2% and 4.3 MPa, respectively. Figure 12 shows the comparison between the experimental and predicted data by equation (19) of VT14 alloy (figures 12(a)–(g)) and the correlation between experimental and fitted flow stress (figure 12(h)). The predicted values are in good agreement with the experimental data, which prove the capability of the constructed model in predicting the flow behaviour of this alloy. The constructed model exhibited similar predictability as far as Arrhenius type models for this alloy in [47, 48].

\[
\begin{align*}
\quad \quad f(e) &= 1 + 0, 0457e^2 - 0, 5e - 0, 15e^3 \\
D_0(T) &= \frac{d_0 \cdot V_0 + d_n \cdot V_n}{\sqrt{d_0 \cdot d_n}} = 125 - 0, 05 \times \exp(0.007 \times T[\degree C]) \\
K(\varepsilon) &= 0, 25 + 2 \times 10^{-5} \times \exp(0.009 \times T[\degree C]) \\
\quad \quad m0 &= 0.35 + 0.09e - 0.24e^2 + 0.15e^3 \\
\quad \quad \theta &= -14.5 + 5.3 \times \exp(0.8 \times e)
\end{align*}
\]

The predictability of the constructed model was assessed using the same standard statistical quantities which stated in equations (14)–(16). The values of R, AARE and RMSE for this alloy were 0.97, 7.2% and 4.3 MPa, respectively. Figure 12 shows the comparison between the experimental and predicted data by equation (19) of VT14 alloy (figures 12(a)–(g)) and the correlation between experimental and fitted flow stress (figure 12(h)). The predicted values are in good agreement with the experimental data, which prove the capability of the constructed model in predicting the flow behaviour of this alloy. The constructed model exhibited similar predictability as far as Arrhenius type models for this alloy in [47, 48].

3.5. Cross-validation
In order to evaluate the prediction accuracy of the flow behavior of the investigated alloys under superplastic deformation, the cross-validation technique was applied. The cross validation method is explained in details in [46]. The experimental curves were extracted one by one, and the model subsequently rebuilt, then the excluded conditions were predicted and compared with the experimental results. Figure 13 shows the experimental flow stress (line) and the predicted via the constructed models after cross validation (points) for the VT6 (figure 13(a)), OT4-1 (figure 13(b)) and VT14 (figure 13(c)) alloys. Figure 13 proves that the predicted flow stress values after the cross validation are in a good agreement with the experimental values for studied alloys.
4. Conclusion

In the present study, the flow behaviour of VT6, OT4-1 and VT14 titanium alloys were modelled in a temperature and strain rate range of the superplastic deformation. The investigated alloys have different microstructure leading to different flow behaviour characteristics. VT6, OT4-1 alloys were characterised by strain hardening, while VT14 alloy was characterised by strain softening. Therefore, the microstructural parameters of each alloy were included in the proposed models.

The predictability efficiency of the constructed models was evaluated via R, AARE and RMSE, statistical comparative parameters. The values of R, AARE and RMSE for VT6 alloy were 0.98, 5.7% and 2.8 MPa, respectively. And for OT4-1 alloy were 0.95, 5.2% and 1.1 MPa, respectively, for VT14 alloy were 0.97 MPa, 7.2% and 4.3, respectively. The constructed models were assessed via the cross-validation approach which proves the excellent capability in predicting the superplastic flow behaviour of the investigated alloy.

Acknowledgments

The authors wish to dedicate the work to the memory of Prof. Vladimir K Portnoy. We are thankful for his guidance and support of this study.

The study of VT6 and OT4-1 alloys was financially supported by the Ministry of Science and Higher Education of the Russian Federation in the framework of State task for Universities [project no. 11.7172.2017/8.9] for. All experiments made with VT14 alloy were financially supported by Russian Science Foundation [Grant #18-79-00348].

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

The study of VT6 and OT4-1 alloys was financially supported by the Ministry of Science and Higher Education of the Russian Federation in the framework of State Task for Universities [project no. 11.7172.2017/8.9] for. All experiments made with VT14 alloy were financially supported by Russian Science Foundation [Grant #18-79-00348].

ORCID iDs

A O Mosleh https://orcid.org/0000-0002-0247-7975

References

[1] Rugg D, Dixon M and Burrows J 2016 High-temperature application of titanium alloys in gas turbines. material life cycle opportunities and threats—an industrial perspective Mater. High Temp. 33 536–41
[2] Singh P, Pungotra H and Kalsi N S 2017 On the characteristics of titanium alloys for the aircraft applications Mater. Today Proc. 4 8971–82
[3] Antolovich S D, Busso E P, Skelton P and Telesman J 2016 High temperature materials for aerospace applications Mater. High Temp. 33 289–90
[4] Sieniawski J and Motyka M 2007 Superplasticity in titanium alloys J. Achiev. Mater. Manuf. Eng. 24 123–30
[5] Boyer R R 1995 Titanium for aerospace: rationale and applications Adv. Perform. Mater. 2 349–68
[6] Lelyens C and Peters M 2002 Titanium an Titanium Alloys (England: Wiley)
[7] Moiseyev V N 2006 Titanium Alloys: Russian Aircraft and Aerospace Applications CRC Press (Boca Raton, FL: CRC Press)
[8] Nieh T G, Wadsworth J and Sherby O D 2014 Superplasticity in Metals and Ceramics (Cambridge: Cambridge University Press)
[9] Mosleh A O, Mikhailovskaya A V, Kotov A D and Kwame J S 2019 Experimental, modelling and simulation of an approach for optimizing the superplastic forming of Ti-6%Al-4%V titanium alloy J. Manuf. Process. 45 262–72
[10] Mosleh A O, Mikhailovskaya A, Kotov A D, AbuShanab W, Moustafa E and Portnoy V 2018 Experimental investigation of the effect of temperature and strain rate on the superplastic deformation behavior of Ti-based alloys in the ($\alpha + \beta$) temperature field Metals (Basel) 8 819
[11] Langdon T G 1991 The physics of superplastic deformation Mater. Sci. Eng. A 137 1–11
[12] Kawasaki M and Langdon T G 2018 Superplasticity in ultrafine-grained materials Rev. Adv. Mater. Sci. 54 46–55
[13] Roy S and Swamin S 2013 The influence of temperature and strain rate on the deformation response and microstructural evolution during hot compression of a titanium alloy Ti-6Al-4V-0.1B J. Alloys Compd. 548 110–25
[14] Zhao W J, Ding H, Song D, Cao F R and Hou H L 2007 The effect of grain size on superplastic deformation of Ti-6Al-4V alloy Mater. Sci. Forum 551–552 387–92
Mater. Res. Express 7 (2020) 016504

A O Mosleh et al.

[15] Luo J, Ye P, Li M Q and Liu L Y 2015 Effect of the alpha grain size on the deformation behavior during isothermal compression of Ti-6Al-4V alloy Mater. Des. 88 32–40

[16] Souza P M, Hodgson P D, Rolfe B, Singh R P and Beladi H 2019 Effect of initial microstructure and beta phase evolution on dynamic recrystallization behaviour of Ti6Al4V alloy—an EBSD based investigation J. Alloys Compd. 793 467–79

[17] Ghosh A K and Hamilton C H 1982 Influences of material parameters and microstructure on superplastic forming Metall. Trans. A 13A 733–43

[18] Imai H, Yamane G, Matsumoto H, Vidal V and Velay V 2019 Superplasticity of metastable ultra-fine-grained Ti-6242S alloy: mechanical flow behavior and microstructural evolution Mater. Sci. Eng. A 754 569–80

[19] Kotov A D, Mikhal'yovskaya A V, Mosleh A O, Pourcelot T P, Prosviryakov A S and Portnoi V K 2019 Superplasticity of an ultrafine-grained Ti-4%-Al–1%-V–3%-Mo titanium alloy Phys. Met. Metallurg. 120 66–74

[20] Zhe J, Yuhao C, Yanghui Q, Chengjun S and Hongwei L 2018 Effect of deformation of constituent phases on mechanical properties of Ti-6-5Al-3-SiO-1.5Zr-0.5Si titanium alloy Mater. Sci. Eng. A 710 200–5

[21] Wert J A and Paton N E 1983 Enhanced superplasticity and strength in modified Ti-6Al-4V alloys Metall. Trans. A 14 2355–44

[22] Alabert E, Barba D, Shahiev M R R, Murzinova M A A, Galeyev R M M, Valiakhmetov O R R, Aleldinov A F F and Reed R C C 2019 Alloys-by-design: application to titanium alloys for optimal superplasticity Acta Mater. 178 275–87

[23] Alabert E, Konits P, Barba D, Dragnevski K and Reed R C 2016 On the mechanisms of superplasticity in Ti-6Al-4V Acta Mater. 105 449–63

[24] Seshacharyulu T, Medeiros S C, Frazier W G and Prasad Y V R K 2000 Hot working of commercial Ti-6Al-4V with an equiaxed α-β microstructure: materials modeling considerations Mater. Sci. Eng. A 284 184–94

[25] Matsumoto H, Nishihara T, Velay V and Vidal V 2018 Superplastic property of the Ti-6Al-4V alloy with ultra-fine-grained heterogeneous microstructure Adv. Eng. Mater. 20 1–6

[26] Xiao J, Li D S, Li X Q and Deng T S 2012 Constitutive modeling and microstructure change of Ti-6Al-4V during the hot tensile deformation J. Alloys Compd. 541 546–52

[27] Kotov Y G, Lee C S, Shin D H and Semiatin S L 2006 Low-Temperature Superplasticity of Ultra-Fine-Grained Ti-6Al-4V Processed by Equal-Channel Angular Pressing 37 381–91

[28] Gao F, Li W, Meng B, Wan M, Zhang X and Han X 2017 Rheological law and constitutive model for superplastic deformation of Ti-6Al-4V J. Alloys Compd. 701 177–85

[29] Vanderhaven M, Babet R and Verdonk B 2007 Deformation mechanisms of Ti-6Al-4V alloy during tensile behavior at low strain rate J. Mater. Eng. Perform. 16 208–12

[30] Zhang X, Zhang S, Zhao Q, Zhao Y, Li R and Zeng W 2018 In-situ observations of the tensile deformation and fracture behavior of a fine-grained titanium alloy sheet J. Alloys Compd. 740 669–68

[31] Liu Q, Hui S, Tang K, Yu Y, Ye W and Song S Y 2019 Investigation of high temperature behavior and processing map of Ti-6Al-4V-0.11Ru titanium alloy J. Alloys Compd. 787 527–36

[32] Jha J S, Toppo S P, Singh R, Tewari A and Mishra S K 2019 Flow stress constitutive relationship between lamellar and equiaxed microstructure during hot deformation of Ti-6Al-4V J. Mater. Process. Technol. 270 216–27

[33] Tchéin G, Jacquin D, Aldanondo E, Couppard D, Gutierrez-Orrantia E, Girot Mata F and Lacoste E 2019 Analytical modeling of hot behavior of Ti-6Al-4V alloy at large strain Mater. Des. 161 114–23

[34] Wang J, Xu Y, Zhang W and Wang W 2019 A finite-strain thermomechanical model for severe superplastic deformation of Ti-6Al-4V at elevated temperature J. Alloys Compd. 787 1336–41

[35] Lin Y C, Huang J, Jin L H and Chen D D 2018 Phase transformation and constitutive models of a hot compressed TC18 titanium alloy in the α + β regime Vacuum 157 83–91

[36] Jiang Y Q, Lin Y C, Zhang X Y, Chen C, Wang Q W and Pang G D 2018 Isothermal tensile deformation behaviors and fracture mechanism of Ti-5Al-5Mo-1Cr-1Fe alloy in β phase field Vacuum 156 187–97

[37] Mikhal'yovskaya A V, Mosleh A O, Kotov A D, Kwame J S, Pourcelot T, Golovin I S and Portnoi V K 2017 Superplastic deformation behaviour and microstructure evolution of near-α Ti-Al-Mn alloy Mater. Sci. Eng. A 708 649–77

[38] Mosleh A O, Mikhal'yovskaya A V, Kotov A D, Kwame J S and Aksenov S A 2019 Superplasticity of Ti-6Al-4V titanium alloy: microstructure evolution and constitutive modelling Materials (Basel) 12 1736

[39] Velay V, Matsumoto H, Vidal V and Chiba A 2016 Behavior modeling and microstructural evolutions of Ti-6Al-4V alloy under hot forming conditions Int. J. Mech. Sci. 108–109 1–13

[40] Zherebtsov S V, Kudryavtsev E A, Salishev G A, Straumal B B and Semiatin S L 2016 Microstructure evolution and mechanical behavior of ultrafine Ti6Al4V during low-temperature superplastic deformation Acta Mater. 121 152–63

[41] Mosleh A O, Mikhal'yovskaya A V, Antón K D, Maria S, Pierre M-R, Kwame J S and Kwame A O M 2019 Superplastic deformation behavior of ultra-fine-grained Ti-1V-3Al-3Mo alloy: constitutive modeling and processing map Mater. Res. Express 6 096584

[42] Tan Q, Zhan M, Liu S, Huang T, Guo J and Yang H 2015 A modified Johnson-Cook model for tensile flow behavior of 7050-T7451 aluminum alloy at high strain rates Mater. Sci. Eng. A 631 214–9

[43] Zhao Y, Sun J, Li J, Yan Y and Wang P 2017 A comparative study on Johnson-Cook and modified Johnson-Cook constitutive material model to predict the dynamic behavior laser additive manufacturing FeCr alloy J. Alloys Compd. 723 179–87

[44] Lin Y C, Chen X M and Liu G 2010 A modified Johnson-Cook model for tensile behaviors of typical high-strength alloy steel Mater. Sci. Eng. A 527 6980–6

[45] Limbadri K, Krishnamurthy H N, Maruthi Ram A, Saibaba N, Kutumba Rao V V, Murthy N J, Gupta A K and Singh S K 2017 Development of Johnson-Cook model for zircaloys-4 with low oxygen content Mater. Today Proc. 4 966–74

[46] Mosleh A, Mikhal’yovskaya A V, Kotov A, Portocel T, Aksenov S, Kwame J and Portnoi V 2017 Modelling of the superplastic deformation of the near-α titanium alloy (Ti-2.5Al-1.8Mn) using arhenius-type constitutive model and artificial neural network Metals (Basel) 7 568

[47] Mosleh A O, Mikhal’yovskaya A V, Kotov A D and Portnoi V K 2018 Arhenius-type constitutive equation model of superplastic deformation behaviour of different titanium based alloys Defect Diffus. Forum 385 45–52

[48] Mosleh A O, Mikhal’yovskaya A V, Kotov A D, Sitkina M, Mestre-Rinn P and Kwame J S 2019 Superplastic deformation behavior of ultra-fine-grained Ti-1V-4Al-3Mo alloy: constitutive modeling and processing map Mater. Res. Express 6 096584