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Makale
(Article)

Yüksek Sıcaklıklarda Yüksek Miktarda Yumuşama Eğilimi Gösteren Ti-6Al-4V Alaşımı İçin Yumuşama Modelinin Geliştirilmesi

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Öz
Ti-6Al-4V (Ti6Al4V veya Ti64) alaşımı, ısıl işlem uygulanabilir ticari titanyum alaşımları içerisinde en çok kullanılan alaşımdır. Fakat bu alaşımın oda sıcaklığında şekillendirilmesi çok kötüdür. Neredeyse karmaşık bir parçanın üretimi imkansızdır. Bu alaşımın yüksek sıcaklıklardaki düzgün uzamadan sonraki deformasyonu oldukça yüksektir. Bu çalışmada, daha önce aluminyum-magnezyum alaşımları için geliştirilmiş olan Yumuşama Modeli (YM) iyileştirilerek yüksek sıcaklıklarda yüksek miktarda yumuşama eğilimi gösteren Ti-6Al-4V alaşımının akma eğrisinin tahmin edilebilme kabiliyeti arttırılmıştır. İyileştirilen model Geliştirilmiş Yumuşama Modeli (GYM) olarak adlandırılmıştır. Sonuçlar, Geliştirilmiş Yumuşama Modeli'nin Ti-6Al-4V alaşımı için mevcut Yumuşama Modeli'ne göre daha doğru tahmin yaptığını göstermiştir.
Anahtar Kelimeler: Titanyum, Titanyum Alaşımları, Yumuşama Modeli, Modelleme

Improvement of Softening Model for Ti-6Al-4V Alloy Having a High Softening Tendency at Elevated Temperatures

Abstract
Ti-6Al-4V (Ti6Al4V or Ti64) is the most commercially used heat treatable alloy in titanium alloys. However, room temperature (RT) formability of this alloy is very poor and it is almost impossible to produce complex shaped parts. It has significant post uniform elongation at high temperature deformations. In this study, a previously proposed softening model (SM) for aluminum-magnesium (Al-Mg) alloys was improved in order to increase flow curve prediction capability for Ti-6Al-4V alloy having a high softening tendency at elevated temperatures. The improved model was called as Improved Softening Model (ISM). Results indicate that the ISM has more accurate prediction than the SM for Ti-6Al-4V alloy.
Keywords: Titanium; Titanium Alloys, Softening Model; Modelling.

1. INTRODUCTION

Titanium and titanium alloys are technologically important materials for aerospace industry. They have very high strength with respect to specific weight, high corrosion and thermal resistances. Ti-6Al-4V (Ti6Al4V or Ti64) alloy is most commonly used alloy in all titanium materials. This alloy contains 6% aluminum and 4% vanadium in its chemical composition and possesses alpha-beta

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phases at different temperature level. It is considered as a relatively lightweight material. Compared to aluminum, it is 60% heavier while it is 45% lighter than steel. Although T64 has very attractive material properties, its formability at room temperature (RT) is very poor. It is almost impossible to produce complex shape aerospace parts from Ti64. It is a known fact that this alloy has high formability at high temperatures [1]. When Ti64 alloy was formed above 500 ^{o}C, its formability is significantly increased [2]. In addition to improvement in its formability, springback issue can also be eliminated with increasing the forming temperature. Flow curve prediction under various temperatures is an important challenge in order to utilize them in finite element simulation software. The accuracy of finite element analysis (FEA) software results directly depends on the built in or user defined materials models in finite element software. Several attempts have been made by numerous researchers [3-12] for different materials. The modeling of the materials' behavior under different forming conditions is quite important. Successful modeling affects finite element simulation results significantly. As it is known that the flow curve model is one of the most important material models, which is used in the plasticity algorithms to determine stresses during the forming simulations. There are two common material models. The quasi-static models that only depend on the given deformation are called as the quasi-static models. The models called as dynamics include the effects of temperature and strain rates. Dynamic models are most commonly used and implemented models into the FEA are given as following:

One of the most commonly used materials hardening model is the Cowper and Symonds [13] model. This model is reflecting the effects of the deformation at different deformation rates. The contribution of these variables into the stress is controlled with 5 material constants. However, in case the both temperature and strain rate effects need to be included. The mathematical form of the model is as follow:

$$\sigma(\varepsilon,\dot{\varepsilon}) = (C_1 + C_2\varepsilon^{C_3})\left[1 + \left(\frac{\dot{\varepsilon}}{C_4}\right)^{\frac{1}{C_5}}\right] \quad (1)$$

Johnson-Cook (J-C) [14] dynamic model is the most preferable and widely used for the forming simulations particularly in non-isothermal analysis. This model can be defined as

$$\sigma(\varepsilon,\dot{\varepsilon},T) = (C_1 + C_2\varepsilon^{C_3})\left[1 + C_4 \ln\left(\frac{\dot{\varepsilon}}{\varepsilon_0}\right)\right]\left[1 - \left(\frac{T - T_0}{T_m - T_0}\right)^{C_5}\right] \quad (2)$$

In the J-C model, C_1 is the initial yield stress at RT. Where $\dot{\varepsilon}$ is the equivalent plastic strain rate and normalized with the reference strain rate $\dot{\varepsilon}_o$. T_o is the RT. T_m and T are the melting and test temperatures of the material, respectively. n represents strain hardening. In the model, the m denotes the effect of thermal softening behavior. C indicates the strain rate sensitivity.

Zerilli-Armstrong [15] developed a constitutive model similar to J-C which considers materials crystal structures. The model is established on dislocation-mechanics theory. The Zerilli-Armstrong model aims to represent the flow curve of the materials which have BCC and FCC crystal structures.

The model includes effects of temperature and strain rate. Eqs. (3) and (4) show the models for BCC and FCC lattice structures, respectively.

$$\sigma(\varepsilon,\dot{\varepsilon},T) = (C_1 + C_2\varepsilon^{C_3}) + C_4\exp(-C_5T + C_6T\ln(\dot{\varepsilon})) \quad (3)$$

$$\sigma(\varepsilon,\dot{\varepsilon},T) = (C_1 + C_2\varepsilon^{C_3})\exp(-C_4T + C_5T\ln(\dot{\varepsilon})) \quad (4)$$

As mentioned earlier that the Softening Model (SM) [12] was originally proposed for aluminum-magnesium (Al-Mg) alloys. This model is well-established for flow curves at different temperature and strain rates. The model predicts the softening behavior of the materials, which have softening tendency at warm and high temperatures. It was tested for several other materials as examples of *Mg* alloys and AHSS [16, 17]. The outcome was quite acceptable. The softening model [12] can be described in mathematical form shown below.

$$\sigma_f(T,\dot{\varepsilon}) = C(T,\dot{\varepsilon})\varepsilon^{n(T,\dot{\varepsilon})}\exp(\lambda\log(T) - T_h\varepsilon) \quad (5)$$

$$C(T,\dot{\varepsilon}) = C_0 + a_1\left[1 - \exp\left(a_2\frac{T-273}{T_m}\right)\right] + a_3\log\left(1 + \frac{\dot{\varepsilon}}{\dot{\varepsilon}_{ref}}\right) \quad (6)$$

$$n(T,\dot{\varepsilon}) = n_0 + b_1\left[1 - \exp\left(b_2\frac{T-273}{T_m}\right)\right] + b_3\log\left(1 + \frac{\dot{\varepsilon}}{\dot{\varepsilon}_{ref}}\right) \quad (7)$$

Where *C* and *n* values represent the strength coefficient and strain hardening exponent, respectively. Temperature dependency of the given formulations is described by the exponential form and the strain rate effect is described by the logarithmic form. Beside these independent parameters, the equations also consist of the material fitting parameters. These fitting parameters are used to reflect the materials' response against the applied deformations under various conditions. Some of these parameters reflect the temperature magnitudes and some of them reflect the strain rate's magnitude during the forming operations.

In this proposed study, the softening model was modified to improve prediction capability of the model and for expansion for various materials which have high softening tendency at elevated temperature. The improved model was tested for Ti64 alloy.

2. DESCRIPTION OF IMPROVED SOFTENING MODEL (ISM)

As aforementioned before the mostly used flow curve models are able to predict the hardening region of the material response at low or high temperatures. However in most cases, this situation is not valid for the most materials at high temperatures since the post uniform elongation namely softening tendency occurs during the plastic deformation. Mathematical form of these models is not proper for the prediction of the stresses after the tensile strength (The models are mostly valid in uniform deformation region). In order to overcome this issue, the authors developed a softening model. In this extension study, the first version of the softening model was improved to increase the prediction capability at high temperatures where the post uniform elongation has occurred during the deformation. Since the softening model has some trouble in prediction of the yield strength and excessive softening tendency, the model is improved via the adaptation of additional material parameters. The general form of the Improved Softening Model (ISM) is given below.

$$\sigma = (A_1 + A_2(1-exp(A_3\frac{(T-273)}{T_m} + A_4 log(1+\frac{v}{v_{ref}})))\varepsilon^{(A_5 + A_6(1-exp(A_7\frac{(T-273)}{T_m})) + A_8 log(1+\frac{v}{v_{ref}}))}$$

$$exp\left[A_9 log(\frac{(T-273)}{T_m}) - A_{10}\frac{(T-273)}{T_m}\varepsilon\right] \quad (8)$$

In the given equation, total of 10 material parameters (A_1,….A_{10}) are used to fit this equation to experimental data at various temperature and strain rates. In this equation, T, v, and ε are temperature, strain rate, and strain, respectively. In the SM**,** strength coefficient C_0 and n_0 are determined by using the power law equation, however in the ISM, these values are also used as the fitting parameters. Additionally, in order to predict the aggressive softening tendency of some materials at high temperatures, the mathematical form *exp* is developed via the addition of A_{10} material parameters and $log((T-273)/T_m)$ instead of $\log(T)$.

The validation of the ISM is made for Ti64 alloy at 0.005 s^{-1} strain rate and several temperatures which are varied from RT to 650 ^oC. The experimental data are read from the literature [18] and depicted in Figure 1.

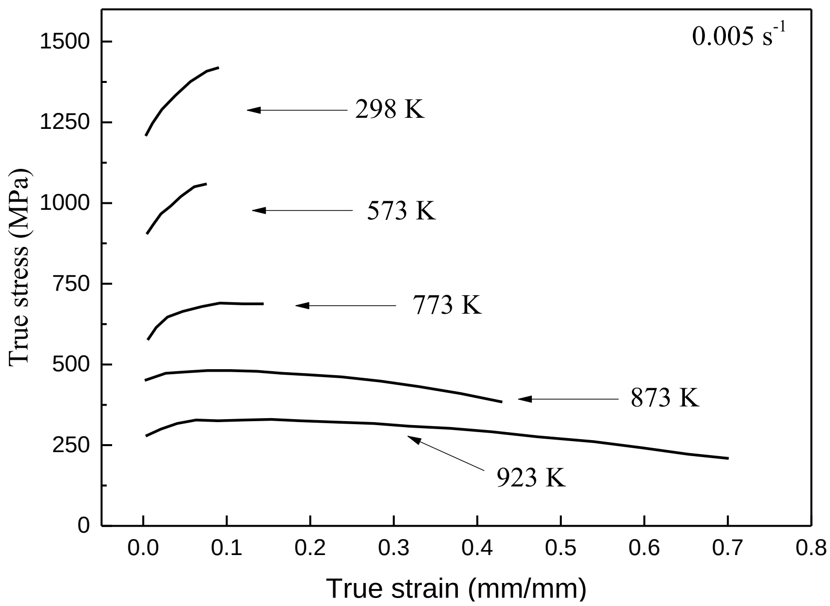


Figure 1: Experimental tensile test results of Ti64 alloy at various temperatures

In this figure, Ti64 alloy shows th**e** hardening characteristics up to the 773 K, however besides the hardening, softening behavior (post uniform elongation) is seen at 873 and 923 K.

3. RESULTS AND DISCUSSION

In this study, material characteristics of the Ti64 alloy were determined by dividing the experimental data in two regions in order to fit the model to the experimental curves more precisely. Because it can be seen from the Figure 1, softening behavior of the material starts to exhibit at 873 and 923 K. Therefore, the parameters are determined for $T \leq 773\ K$ and $T > 773\ K$. The material parameters of the softening models are tabulated in Table 1.

Table 1: Material constants for the Softening and Improved Softening Models.

Softening Model (*T<773.15 K*)						
A1	**A2**	**A3**	**A4**	**A5**	**A6**	**A7**
9.3116	18.9277	13510.78	0.5935	-244.23	-9.8683	-0.3033

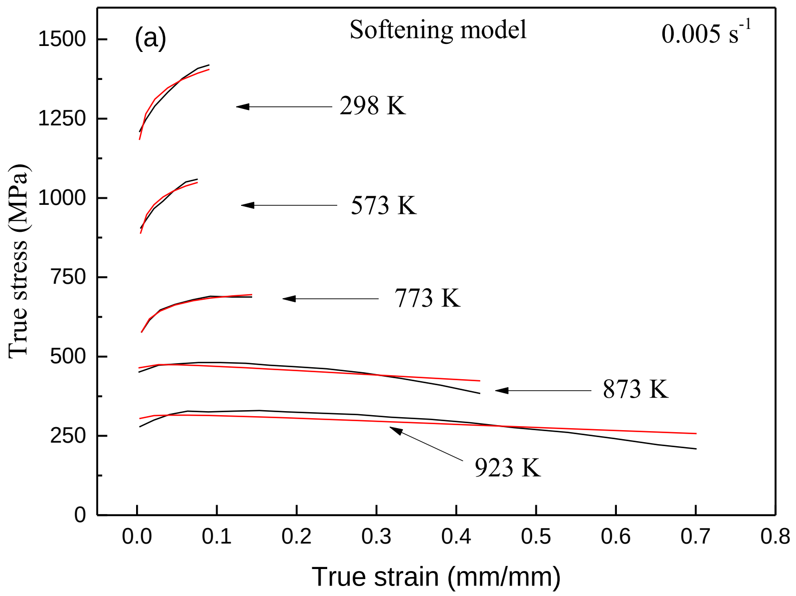
Improved Softening Model (*T<773.15 K*)									
A1	**A2**	**A3**	**A4**	**A5**	**A6**	**A7**	**A8**	**A9**	**A10**
528.4150	292.8434	4.1625	4.9760	-64.883	-0.0916	0.5492	93.6782	-0.010	0.6445

Softening Model (T>773.15 K)						
A1	**A2**	**A3**	**A4**	**A5**	**A6**	**A7**
0.1664	18.8282	828.9319	-0.45011	0.4745	-1.5294	0.0487

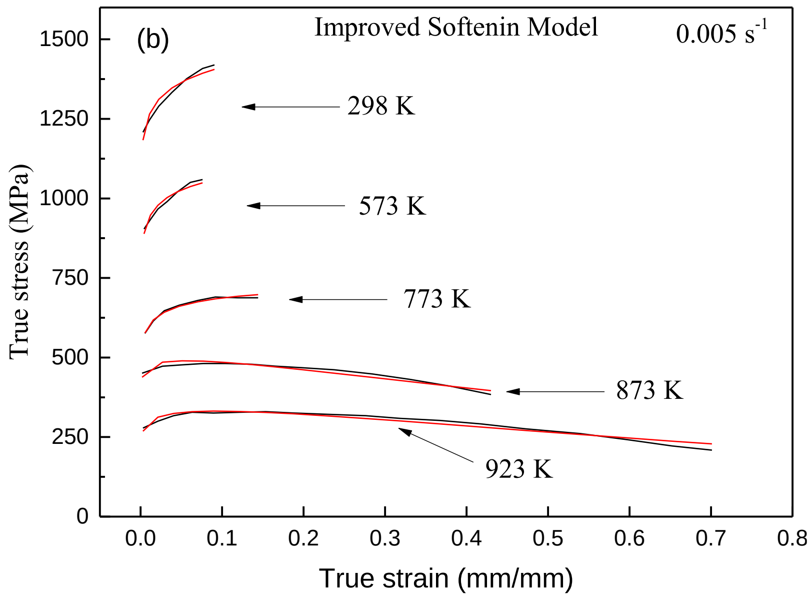
Improved Softening Model (T>773.15 K)									
A1	**A2**	**A3**	**A4**	**A5**	**A6**	**A7**	**A8**	**A9**	**A10**
9.4201	5.0746	-5.982	-0.9457	-3542.18	-0.8501	0.8794	5109.885	-3.939	2.2004

Using the material constants in the model, true stress vs. strain curves were plotted with experimental curves to verify the prediction accuracy. The predicted flow curves shown in Figure 2(a, b) represent the SM and ISM at prescribed temperature values and strain rate. The Figure 2a indicates that although the softening model exhibits high accurate prediction at the temperatures smaller than the 773 K, the prediction capability for the initial stage of the deformation deteriorates with increasing the temperature. It means that the yield strengths which are the stress levels of the initiation of the plastic deformation of the material are over predicted by the model. Additionally, agreement between the model results and the material experiments has shown an aggressive softening tendency at 873 and 923 K which is not satisfactory.

As seen in Figure 2b, although the predictions of the improved softening model is very close to the softening model at the temperature levels lower than 773 K, at higher temperatures there is an agreement between the experimental results and softening model. As a measure of the statistical affinity of the studied models of the SM and ISM are R=0.998 and 0.999, respectively for the temperatures T≤773 K and R= 0.95 and 0.995 respectively for the temperatures T>773 K.



(a)



(b)

Figure 2: Prediction capability of the Softening Model (a) and the Improved Softening Model (b).

The predicted yield strengths of the material at high temperatures are illustrated at Figure 3. As seen from this figure, the prediction results of the ISM are more compatible with the experimental results than the SM results. Approximately 10 MPa low predictions are obtained at 873 and 923 K. Besides the yield strength comparison, the general stress residuals between models and experiments at 873 K and 923 K are depicted in Figure 4 (a-b). Figure 4-a and b show the SM and ISM residuals, respectively. As seen from the figures, the residuals of the SM are higher than the ISM and they varied from -50 MPa to 30 MPa. However the ISM prediction residuals are varied from -20 MPa to 15 MPa. The amounts of these residuals of ISM are also lower than those of SM's.

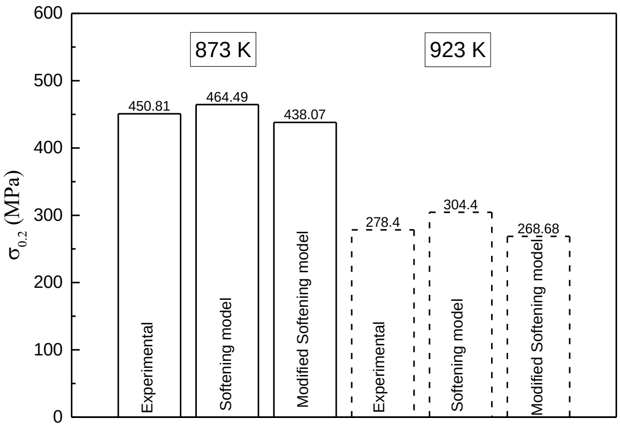
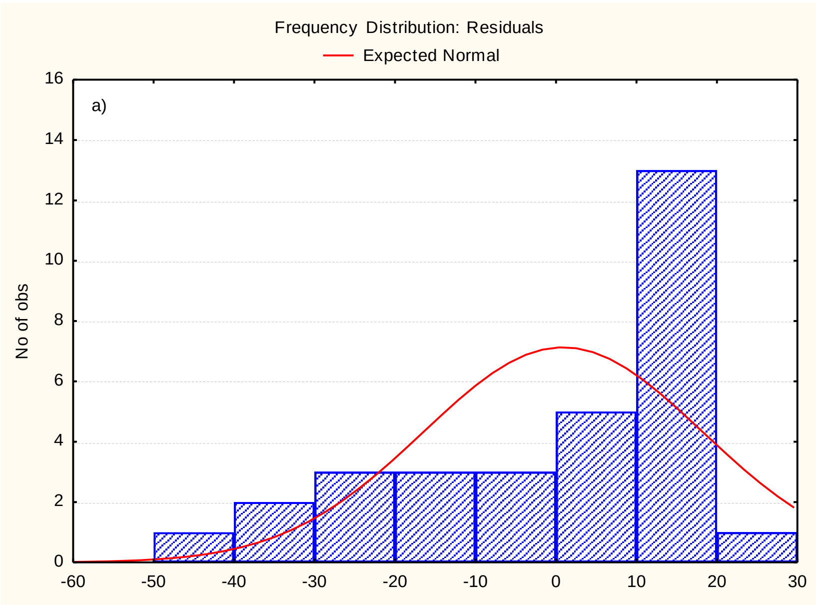
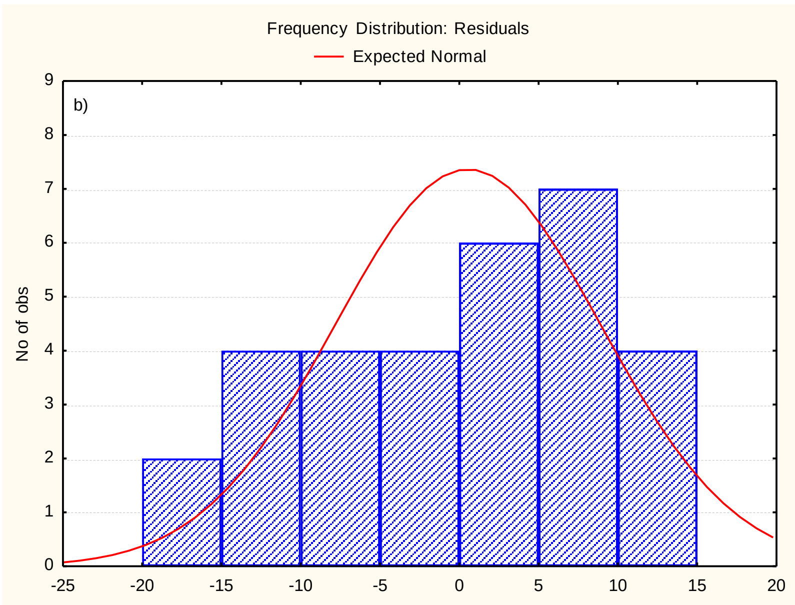


Figure 3: Comparison of predicted and experimental yield strength.



(a)



(b)

Figure 4: The residual distributions of the SM and ISM.

4. CONCLUSION

In this study, an improved version of the SM was proposed. The performance of the SM and ISM were determined for Ti64 alloy at different temperature levels. The main accomplishment of the improved softening model is to predict the softening tendency of the materials at high temperature levels. Ti64 alloy exhibits the softening tendency above 773 K and the model fits to this tendency with a good agreement. However, particularly at the initial stage of the deformation, the prediction is not satisfactory. The ISM has more accurate results than SM.

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