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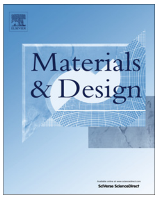

Constitutive modeling and the effects of strain-rate and temperature on the formability of Ti–6Al–4V alloy sheet

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ABSTRACT

The constitutive model considering the strain-rate and temperature effects was presented by fitting the true stress–strain curves of Ti–6Al–4V alloy over a wide range of strain-rates (0.0005–0.05 s^{-1}) and temperatures (923–1023 K). The Forming Limit Curve (FLC) of Ti–6Al–4V alloy at 973 K was measured by conducting the hemispherical dome test with specimens of different widths. The forming limit prediction model of Ti–6Al–4V alloy, which takes strain-rate and temperature sensitivity into account, was predicted based on Marciniak and Kuczynski (M–K) theory along with Von Mises yield criterion. The comparison shows that the limit strain decreases with temperature lowering but strain-rate increasing. The comparison between theoretical analysis and experiment of FLC verifies the accuracy and reliability of the proposed methodology, which considers the strain-rate and temperature effects, to predict limit strains in the positive minor strain region of Forming Limit Diagram (FLD).

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1. Introduction

Since the emergence of titanium and its alloys in the early 1950s, they have been extensively used in aerospace, defense, energy and medical industries [1]. For example, titanium and its alloys have been widely utilized in the aerospace components such as structural airframe and engine components, because of the excellent strength to weight ratio, outstanding resistance to corrosion and inherent thermal compatibility with composite materials [2]. Additionally, the application of titanium in medicine, such as artificial joints and dental implants, is more and more extensive [1]. This is mainly because of its excellent properties, such as high strength, light weight, resistance to corrosion, bio-compatibility and low modulus [3].

However, the formability of titanium alloys is unsatisfactory at room temperature. Compared with other traditional metallic materials, titanium alloy components are more difficult to form. They exhibit a high degree of springback, and the lower formability causes the material to crack or tear easily during forming processes at room temperature [4].

Therefore, there is increasing attention and interest to investigate the formability of titanium alloys [5]. Several studies have been performed to research the formability of titanium alloys at room temperature. Lang et al. investigated the cold forming behavior of Ti–15–3–3–3 based on simulation and experimental verification [6]. A numerical simulation method was developed by Jurendić et al. for the deep drawing process of α-titanium alloy sheet using LS-Dyna [7]. Esfahlan et al. investigated a new method of deep drawing assisted by floating disk for Ti–6Al–4V both in experimental and simulation [8]. Satoh et al. investigated the ability and behavior of two kinds of pure titanium and one of its alloy in the stretch-drawing process [9]. It is observed that the formability of titanium alloy sheets could be greatly improved by hot forming. Lai et al. investigated the effects of tooling temperatures on the formability of Ti-TWBs at elevated temperature. The results revealed that the formability of Ti-TWBs can be enhanced by elevated tooling temperatures [10]. It was found that the formability of both the Ti-TWBs and their base metal increases with increasing forming temperature in the study of Cheng et al. [11]. In the study of Chen and Chiu, the formability of commercially pure titanium sheets at various temperatures was studied by the experimental approach. The results obtained from the V-bend tests revealed that springback can be reduced at elevated forming temperature [12]. The experimental results from Lai et al. revealed that the ductility of Ti–6Al–4V was enhanced at higher working temperatures, because of a decrease in the yield strength [13]. In the study of Odenberger et al., a set of material tests were performed on Ti–6Al–4V at temperatures ranging from room temperature up to 833 K. The result indicated that the alloy can be formed to higher strain values at 673 K than at room temperature before fracture occurs [14]. Odenberger et al. also indicated that Ti-6242 is suitable to be formed by hot sheet metal forming [15]. However, this process increases the manufacturing cost. Finite element analysis has enjoyed considerable success and popularity in sheet metal forming analyses since

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its introduction. The accuracy and usefulness of simulation depends to a great degree on the accuracy of constitutive model used.

The forming limit, which reflects the largest deformation of the sheet metal before plastic instability, is used to quantitatively describe the formability of sheet metal [16]. It is a significant performance index and process parameter in the field of sheet metal forming. Forming Limit Diagram (FLD), which is introduced by Keeler and Goodwin, is a useful tool to evaluate the formability of different materials [17]. However, the experimental measurement of FLD is a difficult, time consuming and expensive process, especially at elevated temperature. Consequently, considerable effort has been made to construct reliable forming limit prediction models from the perspective of theoretical calculation. Recently several studies have been reported on the constitutive modeling and the formability predictions at elevated temperature using the theoretical Forming Limit Curves (FLCs). In the investigation of Min et al., a prediction model for hot forming limits of steel 22MnB5 was derived based on Storen and Rice's Vertex theory and Logan–Hosford yield criterion, and a calculation model was also established based on Logan-Hosford yield criterion according to Marciniak and Kuczynski (M–K) theory [18]. The FLDs of aluminum alloy 5083 were constructed from the perspective of theoretical calculation and finite element simulation, and the effect of the rate sensitivity index on its formability was evaluated by Zhang et al. [19]. In the study of Khan et al., M–K theory was used to obtain the theoretical strain and stress-based FLCs of AA5182-O at different strain-rates and temperatures [20]. Haghdadi et al. investigated the flow stress behavior of cast A356 aluminum alloy by a set of isothermal hot compression tests. The influence of strain was incorporated in an Arrhenius-type constitutive equation by considering the related material constants as functions of strain [21]. An artificial neural network model was established to estimate the high temperature flow behavior of a cast A356 aluminum alloy [22]. However, much research needs to be done on the forming limit prediction model of Ti–6Al–4V alloy, and the effects of strain-rate and temperature need to be further discussed.

This paper is focusing on the method to obtain theoretical FLC using the Backofen equation, which takes strain-rate and temperature sensitivity into account. The forming limit prediction model is based on M–K theory along with Von Mises yield criterion. Then, the effects of strain-rate and temperature on the formability of Ti–6Al–4V alloy are discussed. The comparison between theoretical FLC and experimental FLC is used to verify the reliability and robustness of the prediction.

Table 1
Chemical composition of as-received Ti–6Al–4V alloy (wt.%).

Material	Al	V	Fe	C	H	O	Ti
Ti–6Al–4V	6.02	3.78	0.08	0.007	0.0082	0.074	Bal.

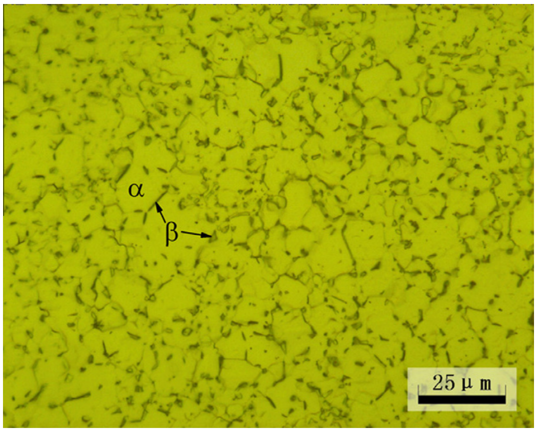

Fig. 1. Initial microstructure of the Ti–6Al–4V alloy sheet [23].

2. Experimental procedures

2.1. Material

The chemical composition of Ti–6Al–4V alloy is listed in Table 1. The as-received alloys were annealed after hot and cold rolling into sheet of 1.5 mm thickness. The initial microstructure is shown in Fig. 1.

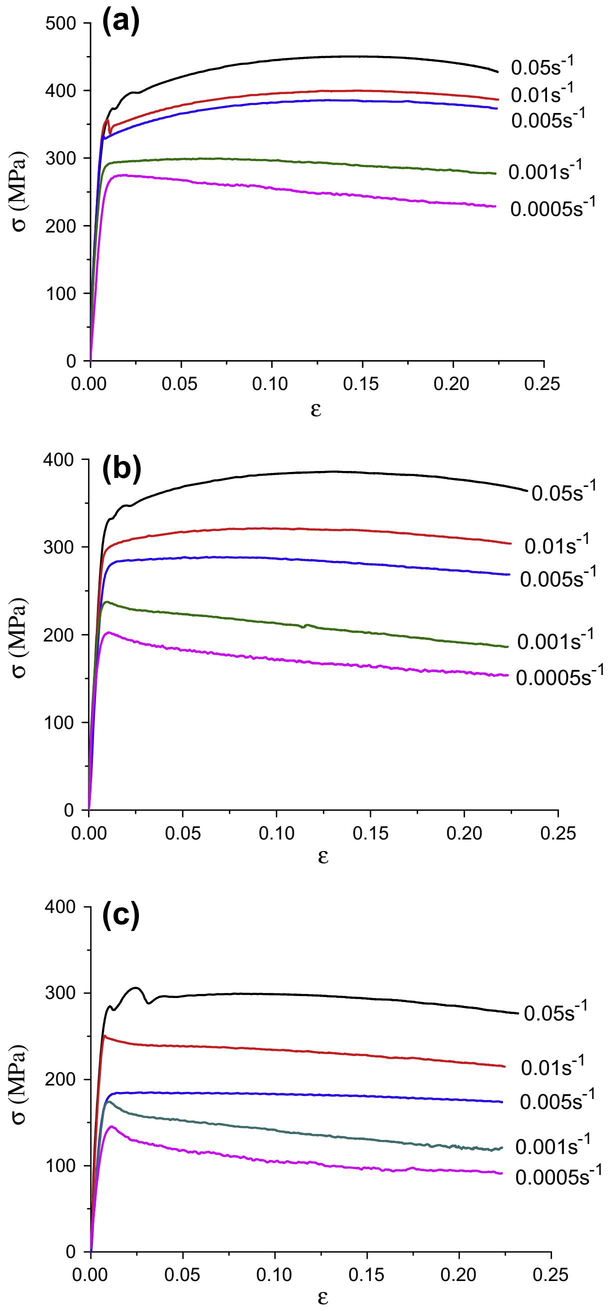

Fig. 2. True stress–strain curves of Ti–6Al–4V alloy under different experimental conditions: (a) 923 K; (b) 973 K and (c) 1023 K.

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