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Research Article

Constitutive Behavior of AZ31 Magnesium Tube Processed by Severe Plastic Deformation

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ABSTRACT

In this study, the evolution of parallel tubular channel angular pressing (PTCAP) as a severe plastic deformation process on the hot deformation behavior of the extruded AZ31 magnesium tube was investigated. After four passes, a more refined and homogeneous microstructure was achieved. To understand constitutive behavior, hot tensile tests were carried out on four passes of specimens at temperatures of 350, 400, and 450ºC with strain rates of 0.0001, 0.001, and 0.01 s^{-1}. The dependence of flow stress on strain rate and temperature was investigated by the Zener-Hollomon equation and the activation energy was found to be around 131.26 kJ/mol. Effect of strain was included in the constitutive equation by applying material constants. Based on the constitutive model, the stress-strain curves of PTCAP processed tubes were extracted and compared with the experimental curves. The results indicate good agreement between experimental and predicted flow curves by considering the softening effect.

1. Introduction

Production of lightweight ultra-fine grained (UFG) tubes with considerable strength, such as Mg alloys, has attracted a great deal of interest in recent years. There are few severe plastic deformation (SPD) techniques specifically designed to produce UFG tubular components including high-pressure tube twisting (HPTT) [1], accumulative spin-bonding (ASB) [2], tube cyclic expansion-extrusion (TCEE) [3], tubular channel angular pressing (TCAP) [4], and parallel tubular channel angular pressing (PTCAP) [5]. The main advantages of PTCAP over other methods are lower required loads during the process and homogenous strain distribution in both radial and axial directions. In this process, a considerable plastic strain is imposed to a specimen while keeping the sample's cross-sectional dimensions [6]. It has been observed that applying high temperatures during the deformation of magnesium-based alloys considerably improves their formability and workability due to the activation of more slip systems [7]. To study the hot deformation behavior of PTCAPed Mg alloys in different modes, including tension [8-10], compression [11], and torsion, can be applied [12]. Constitutive equations can be employed to describe flow stress behavior at elevated temperatures. Flow stress depends on different factors including material composition [10], microstructure [13, 14], and

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deformation conditions [15]. Therefore, for a given material the shape of the flow stress curve is primarily influenced by deformation mode, strain rate, and temperature [16]. The activation energy, Q, is defined as the minimum energy required for deformation to happen which can be calculated by using series of flow stress information [17, 18]

So far, a small number of studies have focused on the hot tensile behavior of Mg-based alloys and related constitutive equations. Takuda et al. [19] were among the first to develop a comprehensive equation for calculating flow stress as a function of strain rate and temperature, based on Zener-Hollomon, during the hot deformation process of AZ31. In a later study [20], an improved formula was developed in terms of some material constants including the work-hardening exponent, the strain rate sensitivity exponent, and the stress coefficient. Liu et al. [8] investigated the flow stress characteristics of twin-roll-cast AZ31B magnesium alloy and used a modified Arrhenius equation with the hyperbolic sine of temperature to calculate activation energy. Arun et al. [17] studied the effect of ECAP, as a grain refinement technique, on the hot flow behavior of AZ31B alloys. They reported that activation energy for hot deformation decreased after ECAP, possibly due to a reduction in the grain size. They also expressed a new equation using the Zener-Hollomon parameter and calculated the associated constants.

However, the effect of PTCAP, as a new method of producing fine-grained tubes on hot tensile deformation of extruded AZ31 tubes, and the development of related equations has yet to be studied. As illustrated in the scheme of this process in Fig. 1, one pass of the PTCAP procedure is composed of two half cycles. The applied strain can be calculated from Eq. (1):

$$\bar{\varepsilon}_{TN} = 2N \left\{ \sum_{i=1}^{2} \left[\frac{2\cot(\varphi_i/2+\psi_i/2)+\psi_i \operatorname{cosec}(\varphi_i/2+\psi_i/2)}{\sqrt{3}} \right] + \frac{2}{\sqrt{3}} \ln\frac{R_2}{R_1} \right\} \tag{1}$$

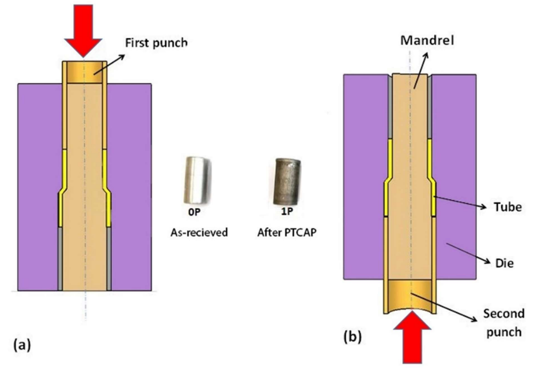

Fig. 1. Schematic illustration of (a) first half pass, (b) second half pass of the PTCAP process and die parameters with as-received and PTCAP processed samples.

where, *N* is the number of passes in PTCAP, φ is the angle between the channels in radians, and ψ is the angle of curvatures [21].

In the present study, the flow stress of AZ31 magnesium alloy tube processed by PTCAP is investigated under uniaxial hot tensile test at different temperatures and strain rates. The deformation activation energy is calculated and material constants for hot deformation are derived. By using the Zener-Hollomon equation, the model for prediction of the flow stress is established and, therefore, a correlation between stress and strain rate is obtained for plastic deformation of AZ31 tubes.

2. Experimental Procedure

The commercially extruded AZ31 magnesium alloy with the chemical composition shown in Table 1 was used in this work. Tubular samples were prepared and PTCAPed at a temperature of 300ºC and speed of 10 mm/min up to four passes with the details provided in the authors' previous work [21, 22]. Schematic PTCAP process and die parameters are shown in Fig. 1. The total equivalent strain after 1 pass, calculated by Eq. (1) with PTCAP parameters is approximately 1.9.

Using SANTAM tensile test machine, hot tensile tests were conducted at different temperatures of 350, 400 and 450ºC with strain rates of 0.001, 0.01, and 0.1 s^{-1}

Table 1. Chemical composition of extruded AZ31

Element	Al	Zn	Mn	Si	Fe	Cu	Mg
Mass (%)	2.93	0.74	0.39	0.02	0.002	0.0015	Bal.

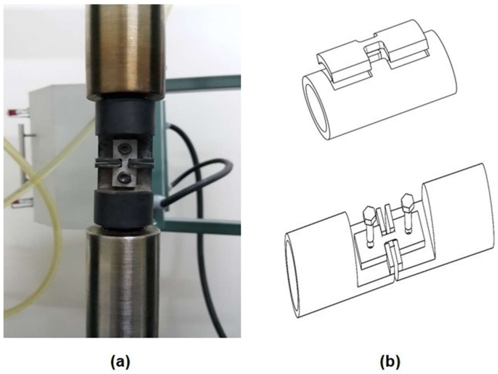

Fig. 2. (a) SANTAM test setting, and (b) schematic of clamping parts for hot tensile test.

on the PTCAPed samples. As shown in Fig. 2, a set of clamping devices was used for the hot tensile tests.

3. Results and Discussion

3.1. Flow stress behavior

Grain refinement, as one of the main advantages, that occurs during the PTCAP process can lead to a fine-grained tube. In this study, the extruded AZ31 was processed with one to four passes PTCAP at 300ºC. The optical microscope was used to study the microstructure of samples (Fig. 3). As illustrated in Fig. 1, PTCAP can cause development of bimodal microstructure in tubes. It is suggested that appearance of small grains between large ones is due to dynamic recrystallization (DRX). The four passes PTCAP tube (Fig. 3(d)) has the smallest bimodal microstructure with an average grain size of ~ 6.8 µm. This sample has a more homogeneous grain structure compared to other samples because the residual coarse grains are significantly consumed during dynamic recrystallization [21]. This tube was further investigated by hot tensile tests.

The hot tensile true stress-strain curves of four passes PTCAP specimen at strain rates of 0.0001, 0.001, and 0.01 s^{-1} and temperatures of 350, 400, and 450ºC are illustrated in Fig. 4(a) to 4(c). As mentioned, flow stress curves are related to deformation conditions. It is well-known that temperature and strain rate are important parameters influencing flow stress and DRX in magnesium alloys. In general, increasing temperature and decreasing strain rate caused the flow stress to decrease making dynamic softening apparent in the flow stress curves due to DRX [23].

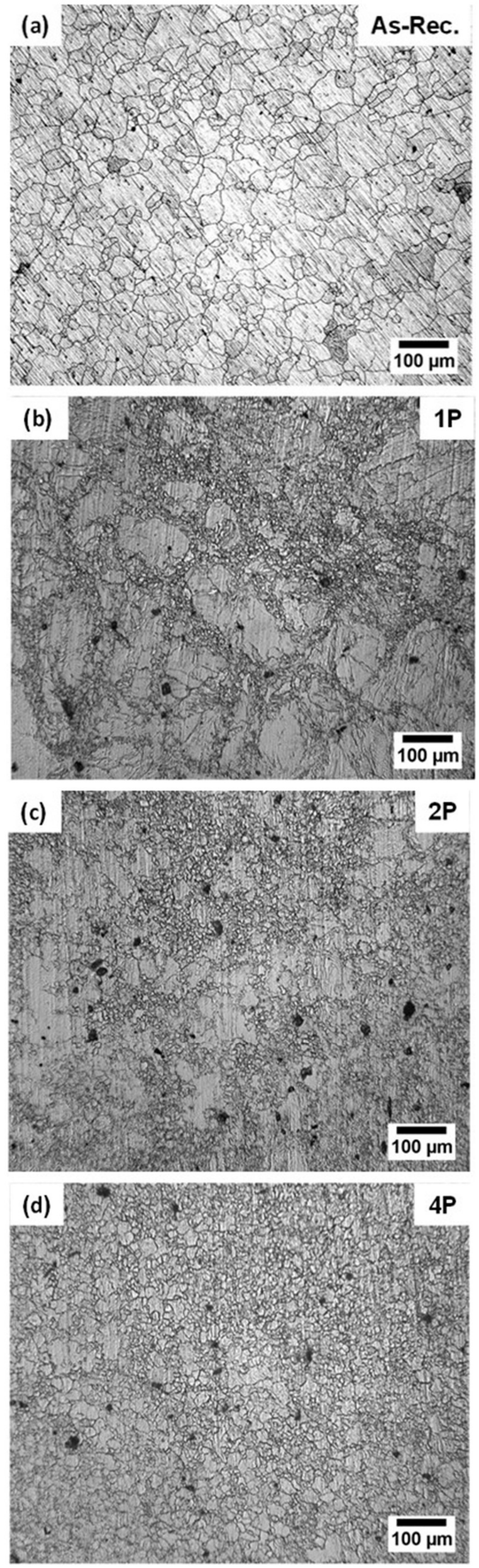

Fig. 3. Optical microscopy studies of (a) as-received sample, (b) one pass, (c) two passes, and (d) four passes PTCAP samples prepared in 300˚C.

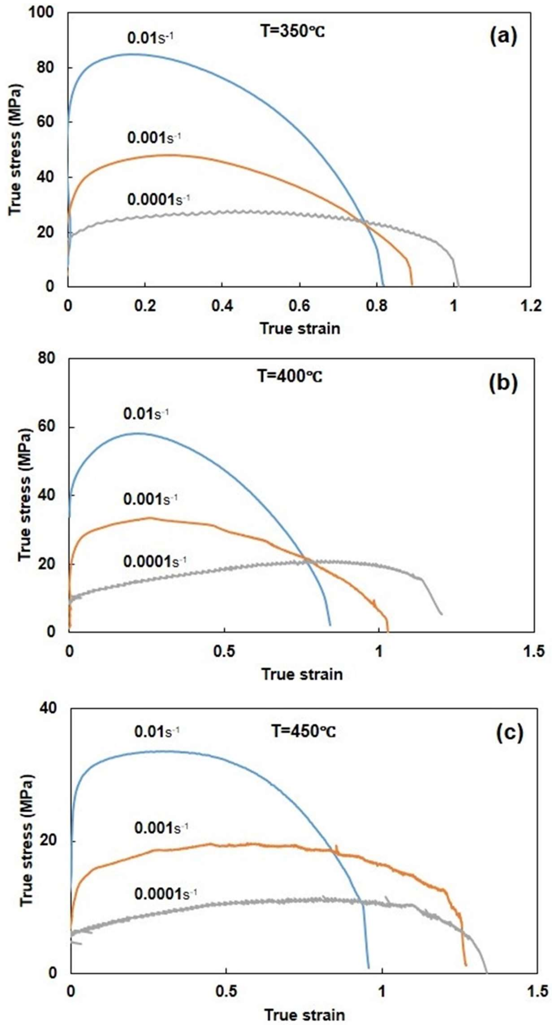

Fig. 4. The true stress-strain curves of four passes PTCAP tubes obtained by hot tensile tests.

Flow stress increases rapidly at the first stage with the increase of strain. This phenomenon results in generation of dislocations that caused the work hardening effect. Flow stress increases smoothly up to a peak. After peak stress, the flow stress reduced rapidly because of the softening effect due to dynamic recrystallization and grain growth [24].

Under tensile test conditions, at lower temperatures and higher strain rates, the stress-strain curves illustrate a work hardening stage at the onset of plastic deformation followed by a rapid softening stage, whereas at the opposite conditions, more uniform flow stresses are observed [7]. Microstructures of specimen after hot tensile testing at the strain rate of 0.001 s^{-1} and different temperatures are illustrated in Fig. 5. It can be seen that by increasing temperature, the grain microstructure becomes coarser and elongated along the direction of the tensile test [25].

The specimen, in lower temperatures (350, 400ºC), experiences higher strain and therefore by dynamic recrystallization in dislocation accumulation tends to create new small grains. In higher temperatures, the DRX mechanism in grain refinement is weak because of rapid grain growth (Fig. 5(d)) [26].

3.2. Constitutive equation

Three equations are commonly used to describe the relationship between flow stress, strain, strain rate, and temperature behavior of metals during hot deformation [27]:

$$\dot{\varepsilon} = \begin{cases} A'\sigma^{n'}\exp\left(\dfrac{-Q}{RT}\right) \\ A''\exp(\beta\sigma)\exp\left(\dfrac{-Q}{RT}\right) \\ A(\sinh\alpha\sigma)^{n}\exp\left(\dfrac{-Q}{RT}\right) \end{cases} \tag{2}$$

where, A, A', A'', n, n', α, β are material constants. The power-law equation is only appropriate for low stress levels. Conversely, the exponential equation is suitable for high stress. The hyperbolic sine can be used for a wide range of temperatures and strain rates [9] and, therefore, we establish this equation for constitutive analysis. In order to calculate Q using hyperbolic sine equation, the logarithm from both sides of the equation was taken into consideration:

$$\ln \dot{\varepsilon} = \ln A + n \ln(\sinh \alpha\sigma) - \frac{Q}{RT} \tag{3}$$

By rearranging Eq. (3), Q can be expressed as:

$$Q = -R\left(\frac{\partial \ln \sinh \alpha\sigma}{\partial \frac{1}{T}}\right)_{\dot{\varepsilon}}\left(\frac{\partial \ln \dot{\varepsilon}}{\partial \ln \sinh \alpha\sigma}\right)_{T} \tag{4}$$

Appropriate value of α is associated with a set of parallel lines of plotting $\ln\dot{\varepsilon}$ versus $\ln\sinh\alpha\sigma$ at different temperatures, so that a value of $\alpha = 0.015$ was obtained. A Similar amount was reported in previous studies [11].

According to Eq. (4), the hot deformation activation energy (Q) can be determined by plotting $\ln\dot{\varepsilon}$ versus $\ln\sinh\alpha\sigma$ and $\ln\sinh\alpha\sigma$ versus (1/T), as shown in Fig. 6

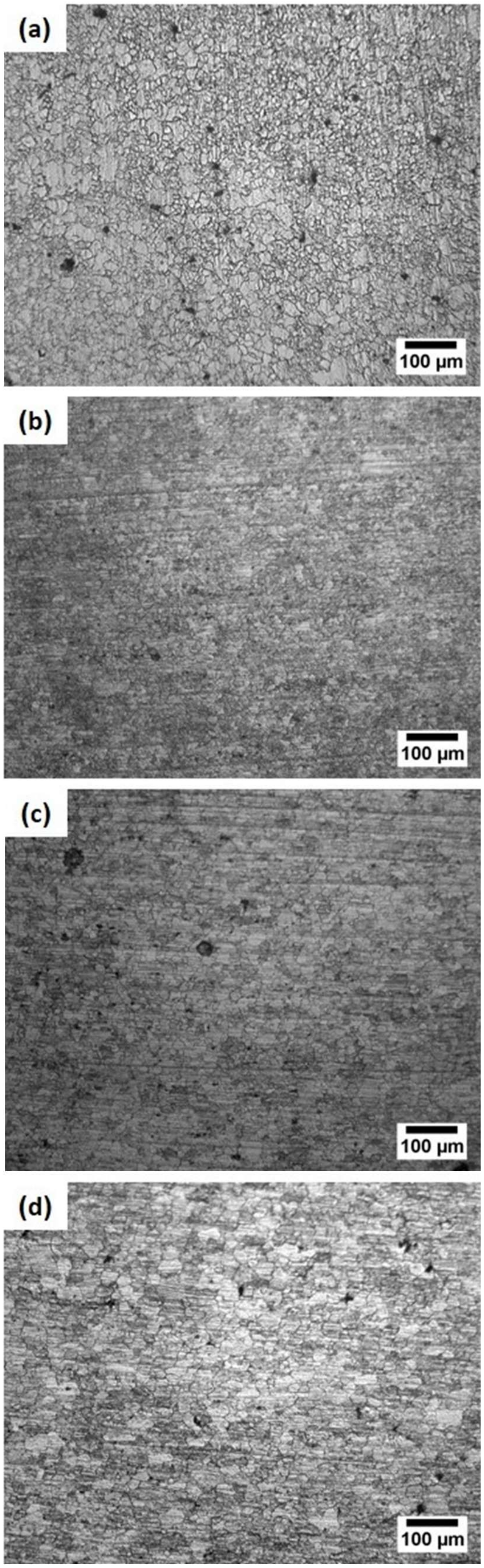

Fig. 5. Optical microstructure of AZ31 magnesium 4th pass of PTCAP after tensile test at fix strain rate of 0.001 s^{-1} and different temperatures: (a) without tensile (b) 350ºC (c) 400ºC (d) 450ºC.

and Fig. 7, respectively. The activation energy is derived from the slope of the straight line plotted in Fig. 8. The parameter n = 3 was calculated from the average slope. According to this approach, the approximate Q-value is 131.26 kJ/mol, which is lower than the self-diffusion activation of magnesium (135 kJ/mol). It has been reported that the amount of Q is related to the number of ECAP passes for magnesium alloys, and can be reduced to 132.3 kJ/mol after three passes. This happens due to the grain refinement which takes place during plastic deformation [17].

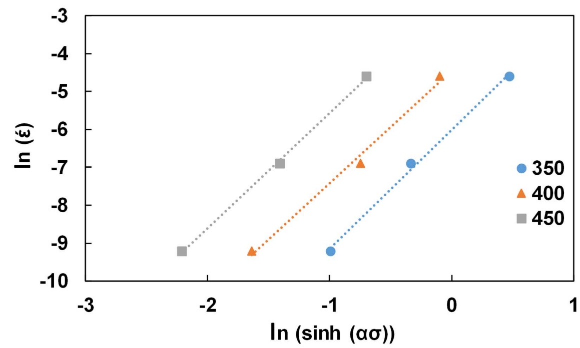

Fig. 6. Relationship plot of $\ln \dot{\varepsilon}$ versus $\ln \sinh \alpha\sigma$ at different temperatures.

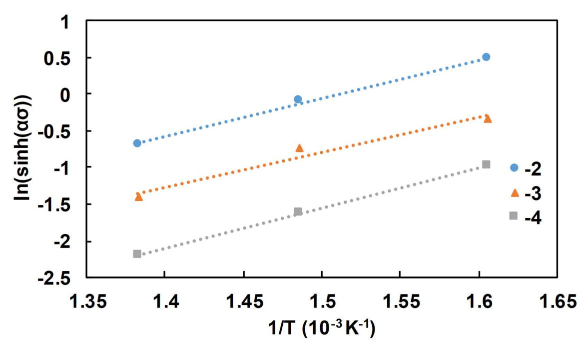

Fig. 7. Relationship plot of (ln sinh ασ) versus (1/T) at different strain rates.

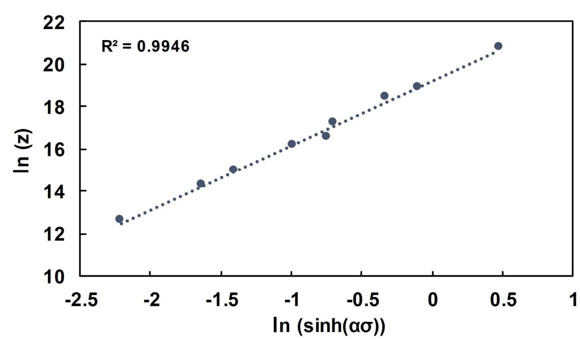

Fig. 8. The curve between $\ln Z$ versus $\ln(\sinh \alpha\sigma)$.

During hot deformation, the relationship between temperature and strain rate is presented in term of the Zener-Hollomon parameter Z [13] as:

$$Z = \dot{\varepsilon}\exp\left(\frac{Q}{RT}\right) \tag{5}$$

In this work, the Zener-Hollomon constitutive equation is employed to analyze the hot deformation behavior. Natural logarithms from $Z = A(\sinh \alpha\sigma)^n$, Eq. (6) is a function in that the slope of $\ln Z$ versus $\ln(\sinh \alpha\sigma)$ corresponds to n and its intercept from origin represents ln A. The results of the linear fit are shown in Fig. 8. The value of $\ln A$ is 19.216 and the average R value was found as 0.9964.

$$Z = A(\sinh\ \alpha\sigma\ )^n \tag{6}$$

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

Therefore, all variables of hyperbolic sine relationship were obtained and stress can be calculated in different strain rates and temperatures. However, the stress-strain diagrams are also a function of strain and it is necessary to study the stress behavior based on strain, therefore all material constants should be determined. To investigate stress based on strain, the value of Q is considered constant and α, n, $\ln A$ could be determined based on the strain that is observed in Fig. 9.

Finally, according to the Zener-Hollomon parameter, and after calculating the variations of material constants, the dependence of flow stress on Z can be expressed as Eq. (7):

$$\sigma = \frac{1}{\alpha}\sinh^{-1}\left[\left(\frac{Z}{A}\right)^{\frac{1}{n}}\right] \tag{7}$$

Fig. 10 illustrates the comparison between experimental flow stress and predicted values by using

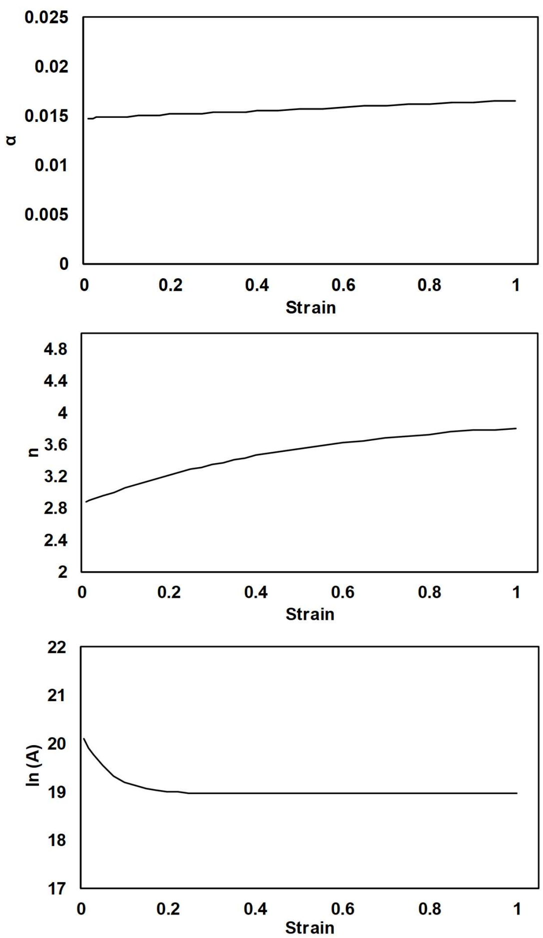

Fig. 9. Material constant based on strain.

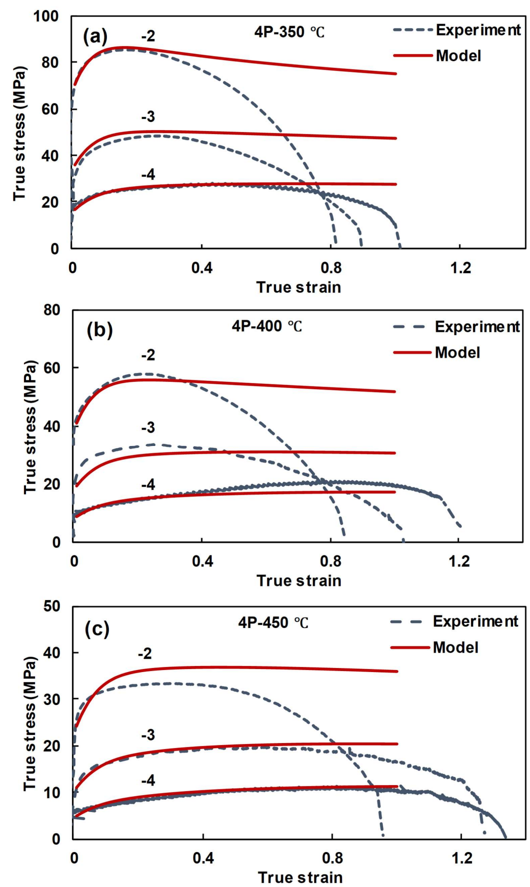

Fig. 10. True tress-strain curves comparison between predicted and experimental extruded AZ31 alloy at different strain rates and temperatures.

dependence of flow stress on strain, strain rate and temperature are calculated for AZ31 magnesium alloy tube. As shown in Fig. 10, the predicted flow stress is in good agreement with experimental results before the instability by necking [28].

4. Conclusion

The hot deformation behavior of the AZ31 magnesium alloy tube processed by the PTCAP was investigated using a hot tensile test at different temperatures and strain rates. The specimens were taken from the tubes prepared by four PTCAP passes, where a more refined and homogeneous microstructure is achieved. The amount of flow stress was calculated at a strain of 0.1. The experimental flow stress curves, up to the instability by necking, were used to develop the constitutive equation of the PTCAPed samples. An activation energy of approximately 131.26 kJ/mol was obtained from the correlation with the experimental results, implying the occurrence of DRX during hot deformation. In addition to the influences of the strain rate and temperature, which were included using the Zener-Hollomon parameter, the dependence of the flow stress on strain was taken into account by the calibration of the constant ln A. It was shown that, aside from the stress drop due to the necking under the tensile test, there is a good agreement between the experimental and predicted flow stresses indicating the reliability of the employed constitutive equation.

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Conflict of Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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