A New Approach for Determining the Optimum Pressure–Time Diagram in Superplastic Forming Process

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Abstract: Superplastic materials show huge amount of deformation in low strain rates and temperature above half of melting point. In superplastic forming, estimating the pressure–time diagram and the thickness distribution has significant importance. Utilizing numerical methods, the involved parameters in superplastic forming can be optimized for such estimations. In the present paper, the simulation of superplastic forming of Ti-6Al-4V alloy for a cup-shape part is demonstrated, assigning the proper constitutive equation. In the following, a noble approach for estimating the pressure–time diagram, using finite element method is presented and by using this approach, the optimum pressure–time diagram for the forming process is estimated, while the effects of process parameters such as friction index and strain rate on pressure–time diagram and thickness distribution is evaluated. Simulation results are compared with other researches results, which confirm satisfactory agreement.

Keywords: Pressure–Time Optimum Diagram, Superplastic Forming, Ti-6Al-4V Alloy

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1 INTRODUCTION

In modern industries, specifically in aerospace and automobile, there is a significant tendency towards materials with high strength to weight ratio. This fact has resulted in designing complicated parts out of magnesium and titanium. To form such materials appropriately, superplastic properties of these materials should be used [1]. Superplasticity is a viscous behavior which only specific metals and alloys with stable and fine microstructure demonstrate it in temperatures above half of melting point [2]. In superplastic forming, such materials show low strength and considerable capacity of elongation. In some special cases, over 2000% elongations have been observed. Superplasticity is identified by low flow stress and high sensitivity of flow stress to strain rate. The simple form of constitutive equation of superplastic materials is presented as follows [3]:

$$\sigma_e = K\dot{\varepsilon}_e^{\,m} \tag{1}$$

In which m and K are material's constant, where m is the index of sensitivity to strain rate which is more than 0.3 in superplastic materials [4].

Titanium alloys are formed mostly in very low strain rates (about 10^{-4} s^{-1}) and in very high temperatures (870-927^{0}C) which is below the phase transfer temperature β [4]. Since low pressure is required for forming process, no spring back problem is observed due to low flow stress. Superplastic properties of material exist only in a limited range of strain rate in which the maximum elongation of material can be obtained. This limited range of strain rate is specified for each material. Therefore, specifying the pressure–time diagram by which the maximum strain rate is kept at optimum value during the process, is crucial.

Temperature and thickness distribution are the other prominent parameters. Thus, to fabricate a part properly, numerical analysis is an appropriate tool for prediction and optimization of superplastic forming. Many superplastic forming processes have been simulated by many researchers [5-11]. In these studies, various effective parameters of the process, including element type, friction coefficient and geometrical shape of the part have been evaluated.

Considering the control of strain rate, several researchers have presented theoretical equations with respect to specific geometrical shapes [12-13]. In complicated geometrical shapes, pressure–time diagram is predicted via simulation which several studies have reported different pressure algorithms [14-17].

In the present study, considering an appropriate constitutive equation, the behavior of the alloy has been modeled. In addition, a new approach is presented in which using UMAT subroutine through ABAQUS software, the proper pressure–time diagram can be calculated. Besides, effective parameters on pressure–time diagram have been also investigated. To validate the simulation results, the outcomes have been compared with other studies.

2 CONSTITUTIVE EQUATION

The utilized constitutive equation in the present study considers the effects of strain rate, grain size, work-hardening of grain growth and work-hardening inside the grains, on the stress. Equation (2) shows the major part of constitutive equation which is the correlation of effective plastic strain rate $\dot{\varepsilon}^p$ with equivalent stress (σ_e), isotropic work-hardening (*R*), grain size (*d*) and yield stress (*k*) [18].

A is the invert of strain rate sensitivity index and γ is the work-hardening of grain growth. Equation (3) expresses the grain size variations during the process with respect to static and dynamic grain growth [19]. Equation (4) demonstrates the work-hardening of the material due to the deformation inside the grains [20].

$$\dot{\varepsilon}^p = ((\sigma_e - R - k)/K)^A d^{-\gamma} \tag{2}$$

$$\dot{d} = \alpha_1 d^{-\gamma_0} + \beta_1 \dot{\varepsilon}^p d^{-\varphi} \tag{3}$$

$$\dot{R} = b(Q - R)\dot{\varepsilon}^p \tag{4}$$

Where α_1 is the static growth parameter of grain size while β_1 is the dynamic growth parameter of the grain size. In this equation, the grain size has different effects on static and dynamic growth of grain growth, which are specified respectively by parameters γ_0, and φ. *K*, *b* and *Q* are materials constants. The values of the constants have been presented in table 1, which are obtained via model calibration through tensile test [18].

3 PRESSURE ALGORITHM

The main objective in modeling of superplastic process is to determine the pressure–time diagram for forming the part in the least time possible so that during the process, the strain rate does not exceed the maximum strain rate of the process. Therefore, the purpose of calculating the pressure is to obtain the optimum strain rate $\dot{\varepsilon}_{opt}$.

Table 1 Material constant indexes for Ti-6Al-4V alloy at 927^0C temperature

γ	A	k	K	b	Q	α_1	β_1	γ_0	φ
2.282	1.400	0.229	60.33	2.854	3.933	73.4	2.155	5.751	0.141

In the present paper, the following approach has been utilized to estimate the optimum pressure in each step of solution based on comparison of strain rate in previous step with optimum strain rate $\dot{\varepsilon}_{opt}$ [21]. In each increment, γ_{max}, defined as the ratio of the maximum equivalent strain rate to optimum strain rate, is calculated:

$$\gamma_{\max} = \dot{\varepsilon}_{\max} / \dot{\varepsilon}_{opt} \tag{5}$$

Considering the fact that all parameters are defined at specific intervals r_{th}, the following algorithm may be utilized for determining pressure at the succeeding interval.

$$\gamma_{\max} < 0.2 \qquad P_{r+1} = 2.0\,P_r \tag{6}$$

$$0.2 \le \gamma_{\max} < 0.5 \qquad P_{r+1} = 1.5\,P_r \tag{7}$$

$$0.5 \le \gamma_{\max} < 0.8 \qquad P_{r+1} = 1.2\,P_r \tag{8}$$

$$0.8 \le \gamma_{\max} < 1.5 \qquad P_{r+1} = 1.0\,P_r \tag{9}$$

$$1.5 \le \gamma_{\max} < 3 \qquad P_{r+1} = P_r / 1.2 \tag{10}$$

$$\gamma_{\max} \ge 3 \qquad P_{r+1} = 0.5\,P_r \tag{11}$$

In which $P_{(r+1)}$ is the new pressure in $(r+1)_{th}$ iteration, and P_r is the previous step pressure in r_{th} iteration. The presented algorithm is fairly simple while its goal is not to obtain the optimum strain rate but to estimate an applicable pressure–time diagram.

4 PROCESS SIMULATION

In superplastic forming, using Argon gas pressure heated sheet is formed into die. Here, superplastic forming process of a cup-shape part has been modeled, using the constitutive model and pressure estimation algorithm presented in section 3 and the results of modeling have been compared with other researches results. Figure 1 illustrates the die and sheet dimensions, where the initial thickness of sheet is 1.25 mm.

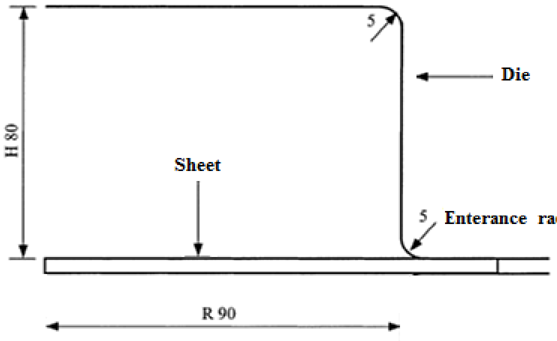

Fig. 1 Die and sheet schematics (dimensions are in mm)

Considering the results of Chen et al., continuum element has the most accurate thickness estimation; and as the geometry of the modeled part is axis-symmetric, the part is simulated axis-symmetric by CAX4R element through simulation software [22]. The die is modeled analytically rigid while the coulomb friction is assumed between die and part. At border conditions, the sheet edge is assumed completely fixed, as demonstrated in Fig. 1. To define the constitutive equation to ABAQUS software (presented in previous sections), UMAT subroutine is used. The algorithm proposed in [23] has been applied in the subroutine. In addition, material constants presented in table 1, have been implemented in the modeling.

To apply the presented pressure algorithm through ABAQUS software, beside UMAT subroutine, UAMP programming is used. Using UAMP subroutine, the new pressure is calculated with respect to the maximum strain rate/optimum strain rate ratio in previous increment and new pressure is applied to the model. To obtain the maximum strain rate in previous increment, URDFIL subroutine is utilized. Table 2 shows the superplastic characteristics of Ti-6Al-4V [24]. In the modeling, the desired strain rate is assumed to be $5\times10^{-4}\,s^{-1}$.

Table 2 Superplastic characteristics of Ti-6Al-4V [4]

Temperature (^{0}C)	870-927
Strain Rate (1/s)	5×10^{-4}-1×10^{-3}
Strain rate sensitivity factor	0.7-0.85
Elongation (%)	750-1170

5 SIMULATION RESULTS

As discussed previously, finite element modelling of superplastic process has been carried out in order to evaluate the effects of different process parameters so which reduced sample parts as well as reduction in production time and higher product quality can be achieved. In this section, the effects of different process parameters on pressure–time diagram and final thickness distribution are discussed. The pressure–time diagram shows the minimum production time with optimum strain rate while final thickness distribution pronounces the quality.

5.1. Thickness distribution comparison

Figure 2 shows the thickness distribution resulted from simulation assuming desired strain rate of 5×10^{-4} s^{-1} and coefficient friction of 0.3. In this figure, other thickness distribution resulted from other researcher has been presented for comparison [22]. Considering this figure, the results from presented modeling are proved to be reliable and the modeling can be applied to evaluate different parameters effects on the process.

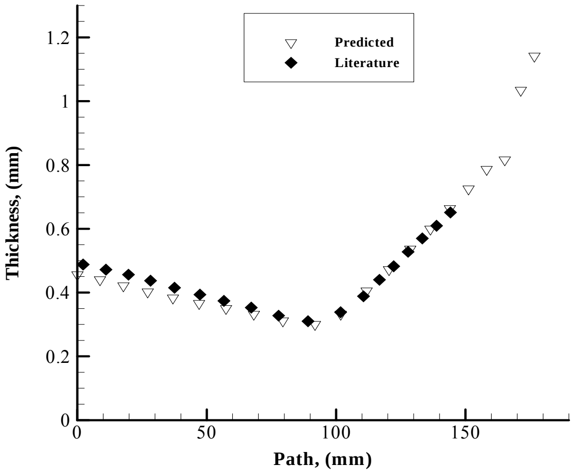

Fig. 2 Comparison of thickness distribution resulted from simulation for cup-shape part with other simulation results

5.2. Friction Effects on Optimum Pressure–time Diagram

Different pressure–time diagrams are plotted for 5×10^{-4} s^{-1} strain rate and various friction coefficients as are demonstrated in Fig. 3. According to Fig. 3, it can be concluded that increasing the friction coefficient, increases the process time while it shows no specific effects on final pressure values. This result is similar to the results stated by Chung Yang [25]. Table 3 presents simulation results in different strain rates and different friction coefficients.

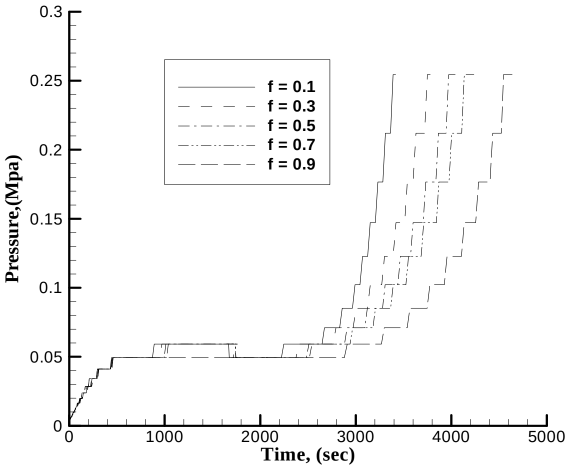

Fig. 3 Various pressure–time diagrams for $5\times10^{-4}S^{-1}$ and different friction coefficients

Table 3 Required times (sec) for forming sheets in strain rates of 2×10^{-4} s^{-1}, 3×10^{-4} s^{-1}, 4×10^{-4} s^{-1} and 5×10^{-4} s^{-1} in different friction coefficients

Strain Rate (s^{-1})	Friction coefficient				
	0.1	0.3	0.5	0.7	0.9
0.0002	9047 s	9569 s	10649 s	11057 s	11360 s
0.0003	5871 s	6518 s	6882 s	7325 s	7536 s
0.0004	4304 s	4753 s	5070 s	5353 s	5498 s
0.0005	3416 s	3808 s	4077 s	4234 s	4635 s

5.3. Strain Rate Effects on Pressure – Time Diagram

To obtain a better understanding towards the effects of strain rate on required forming pressure, pressure–time diagrams for different strain rates have been plotted which are demonstrated in Fig. 4. As it can be seen through diagrams, increasing the strain rate reduces the process time, however, increases the required pressure for forming process. This fact was predictable due to dependency of materials behavior to strain rate.

5.4. The Effects of Friction Coefficient on Thickness Distribution

The effects of friction coefficient of thickness distribution along the sheet have been investigated through different strain rates. The results have been presented in Fig. 5 for 5×10^{-4} s^{-1} in different friction coefficients. As it can be observed through diagrams, by increasing the friction, the thickness uniformity is reduced. This is due to the fact that the materials fluency is reduced after sticking to the sheet due to higher friction coefficients which eventually decreases the thickness uniformity. This result is in agreement with other researchers' results [24].

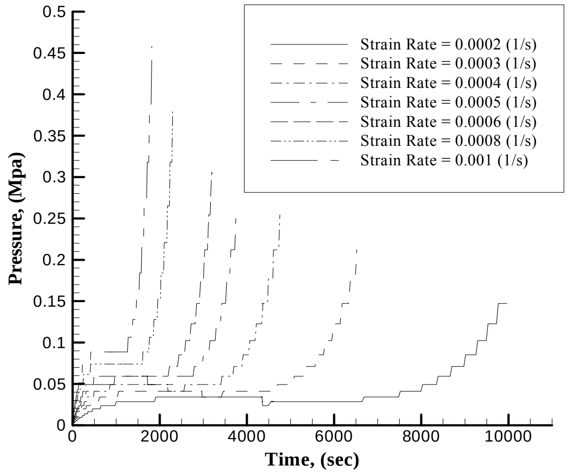

Fig. 4 Pressure–time diagrams for different strain rates and 0.3 friction coefficient

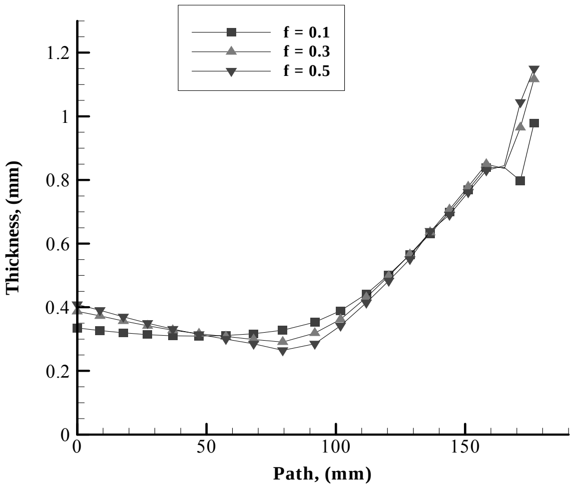

Fig. 5 Comparison of thickness distribution in 5×10^{-4} s^{-1} strain rate and different friction coefficients

5.5. The Effects of Die Entering Radius on Thickness Distribution

One of the effective factors on thickness distribution of the sheet is the die entering radius. Figure 6 illustrates the thickness distribution for radiuses of 1, 3, 5, 8 and 10 mm. According to this figure, increasing the entering radius, materials enter into the die more fluently and therefore, the minimum thickness is increased. On the other hand, material thickness is reduced close to edges.

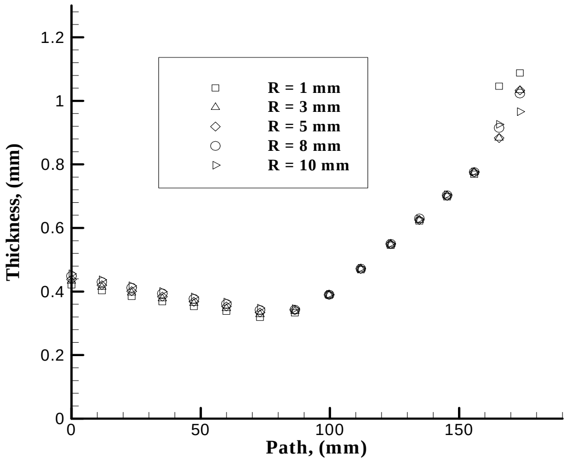

Fig. 6 The effects of die input radius on thickness distribution of the sheet

6 CONCLUSION

In the present paper, superplastic forming of a cup-shape part, made of Ti-6Al-4V alloy has been simulated by finite element method. A new approach in ABAQUS for estimating the optimum pressure has been proposed. The applicable pressure–time diagrams have been plotted for different strain rates and the effects of various parameters on them, have been investigated. The obtained thickness distribution from the optimum pressure–time diagrams, shows a good agreement with other researchers results. The simulation results can be summarized as following:

- Increasing the friction coefficient, increases the process time while the required maximum pressure for forming, has not been changed considerably.
- Increasing the friction coefficient would result in reduced thickness distribution uniformity.
- By increasing the die entering radius, the thickness distribution uniformity is increased.

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