Description of stress-strain response and evaluation of the formability for Al-Cu-Mg alloy under the impact hydroforming

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Abstract. This study aims at investigating on the descriptions of stress-strain response and the assessment of formability for Al-Cu-Mg alloy under impact hydroforming (IHF). IHF process effectively combines the advantages of the flexible liquid and the impact impulse. The formability of low plastic materials can be increased by using IHF process. The elongation of Al-Cu-Mg alloy can even be more than 50 % compared with the quasi-static forming means (27 %~30 %) if the strain rate was on the level of 5000/s. The stress-strain curve is characterized with S-shape. It is found that the strain hardening rate decreases linearly at the stage III, increases linearly at the stage IV and decreases non-linearly at the stage V. The deformation mechanism is the interaction of dislocation accumulation and dynamic recovery under the transmission from non-sheared to sheared precipitation when the strain rate is on the level of 3000/s~5000/s. A modified Kocks-Mecking model was established to describe the mechanical property of AA 2B06. In addition, the high strain rate formability was evaluated by the new means which revealed the relationship between the impact energies, deep drawing height ratios and the deep drawing ratios by using the finite element modelling of the solid liquid coupling.

Keywords: Al-Cu-Mg alloy, impact hydroforming, stress-strain response, modified Kocks-Mecking model, high strain rate formability

1. Introduction

Nowadays, high speed forming methods were attracting more and more attention for they contributed obviously to the increase of the formability especially for some hard-to-form materials, such as Aluminum alloy, Titanium alloy, et al \cite{1-3}. Impact hydroforming was one classical means of high speed forming which possessed the features of flexible effect and impact wave loading \cite{4}. This technology was an effective and potential method for manufacturing the parts used in the fields of aeronautics and astronautics, automobile which characterized with large deformation, locally small and complex structure \cite{5,6}.
It was found that the improvement of the thickness strain could be 62% for AA 5A06 by using the IHF according to the investigation of Ma, et al [4]. In addition, the novel equipment was designed and fabricated based on the investigation on the wave propagation and the fluid-solid coupling. And the aluminum part was successfully manufactured even it has complex structure and double frame by using the IHF which cannot be manufactured by the conventional dropping press and conventional hydroforming [4]. Moreover, the formability of AA 5A06 was evaluated by the means of forming limit curve (FLC) [7].

Formability evaluation was very useful especially for the sheet parts under dynamic forming. However, IHF characterized with both high strain rate and flexible contact which increased the complexity of analyzing the procedure of sheet forming. The procedure was hybrid of deep drawing and hydro-bulging which increased the difficulty of the formability evaluation only by the classical method of forming limit curve [7]. Furthermore, it had to be demonstrated that the contribution of high speed and flexible loading on the formability enhancement, respectively.

The AA 2B06 was a typical Al-Cu-Mg alloy which could be used widely on the structural parts with complicated structure in the field of aeronautics and astronautics. Its formability was very limit only using the conventional forming method such as dropping hammer, stamping and so on. So, the impact hydroforming was an effective method to increase the formability of the Al-Cu-Mg alloy.

Hence, the AA 2B06 alloy was investigated from the aspects of mechanical behavior analysis and characterization based on the modified Kocks-Mecking model. Furthermore, a novel formability evaluation was established by using the finite element modeling based on the solid liquid coupling.

2. The mechanical behavior under impact loading
AA 2B06 is employed to investigate the stress-strain response under the impact loading. It is similar with the AA 2A06 from the aspect of mechanical property and the yield stress is about 58 MPa under the condition of O state. In this section, the mechanical behavior is studied under both the quasi-static and dynamic loading conditions.

2.1. The stress-strain curve
The Electronic universal testing machine and Hopkinson split tensile bar are used to test the quasi-static and dynamic tensile mechanical properties. The stress-strain curves are illustrated in figure 1, which give the difference between the quasi-static and the dynamic loading. The yield and tensile stress are 58 MPa and 168 MPa, respectively. The tensile stress increased to about 175 MPa when the strain rate is 1293/s, and it continually increases when the strain rates are enhanced to 5045/s. From the figure 2, it is found that the elongation increases obviously when the strain rate increases from 3124/s to 3499/s which shows the sensitive range of plasticity enhancement. Moreover, the elongation increases almost linearly when the strain rates are in the range of 1364/s–3124/s. In addition, the stress-strain curve characterizes with S shape when it is under the dynamic loading.

![Figure 1. Stress-strain curve of AA 2B06 under both quasi-static and dynamic loading.](image1)

![Figure 2. Elongation increase under dynamic loading with quasi-static loading.](image2)
2.2. The necking points measurement

The method of Sato is referenced to measure the necking points \[^8\]. The basic principle is judging the beginning point of the obvious change of the strain and strain rate. The means of DIC (Digital image correlation) is employed to measure strain distribution under different strain rates. It is illustrated in figure 3 showing the variation of strain and strain rate with time while taking the sample of 5045/s for example. The strain of axial direction vs strain of transverse direction is illustrated in figure 3(c). As for the center area, the transverse strain increases linearly with the strain of rolling direction when the major strain is less than 0.27. However, two kinds of strain change non-linearly when the strain is larger than 0.27, which demonstrates the beginning of the necking in the local area. It is also found from the results of strain and strain rates as illustrated in figure 3 (a) and (b), the increasing rates of strain and strain rate are different for center area when the time is about 160 μs.

![Figure 3](image)

Figure 3. Determination of the necking point: (a) strain vs time, (b) strain rate vs time, (c) strain of axial direction.

The same method is used to measure the necking points at different strain rates. Then, the whole strain is divided into two part including the strains before and after the necking point. The scale of the range after the necking is calculated and listed in table 1. It is found that the strain of necking increases gradually with the strain rate especially when it is larger than 3124/s. Furthermore, it is about 28% for the scale of the strain after the necking point when the specimen is deformed in quasi-static condition. The scale increases prominently when the strain rate exceeds the level of 3000/s, which is more than 50%. It is illustrated that the material have better ability to resist the necking when the strain rates are in the range of 3000/s~5000/s.

| Strain rate (/s) | The strain at the necking point | The scale of the strain after the necking point (%) |
|-----------------|---------------------------------|--------------------------------------------------|
| 0.001           | 0.193                           | 29.82                                            |
| 0.1             | 0.203                           | 28.01                                            |
| 1293            | 0.172                           | 42.47                                            |
| 3124            | 0.216                           | 55.07                                            |
| 5045            | 0.271                           | 58.31                                            |

3. The description of stress-strain curve

3.1. The strain hardening rate curve

As it is illustrated in figure 4, the stress-strain curves of different strain rates are extrapolated according to the method of Deng et al \[^9\]. By this way, the hardening behavior is obtained especially when the strain is larger than the value of necking point. For the quasi-static loading, the difference is very limited
compared with the original curve, however, it is obvious as for the curves under dynamic loading. This also illustrates the softening procedure under the high strain rates.

![Figure 4](image1.png)  
**Figure 4.** True stress-strain curve obtained by extrapolated method.

![Figure 5](image2.png)  
**Figure 5.** Strain hardening rate curves under different strain rates.

3.2. The description by modified Kocks-Mecking model

The solutes have influence on the work hardening rate according to the investigation of Bouaziz, et al [10]. The Al-Cu-Mg alloy is used in this study, the special phenomenon of strain hardening with S-shape should be studied and explained. The purpose is to establish a model that shows all hardening stages.

The strain hardening rate is defined as $\theta$, which stands for the differentiate of stress and strain.

$$\theta = \frac{d\sigma}{d\varepsilon}$$

(3.1)

The evolution of dislocation with strain for stage III is illustrated as follows according to the classical Kocks Mecking model [11,12]:

$$\theta_{III} = B_{III} - M_{III}\sigma$$

(3.2)

where $\theta_{III}$ stands for the strain hardening rate, $B_{III}$ and $M_{III}$ are the constant.

At the stage IV, the strain hardening rate is as follows:

$$\theta_{IV} = B_{IV} - M_{IV}\sigma$$

(3.3)

where $\theta_{IV}$ stands for the strain hardening rate, $B_{IV}$ and $M_{IV}$ are the constant.

As for the stage V, the strain hardening rate decreases non-linearly. The assumption that $d\rho/d\varepsilon = -\rho^2$ is made to associate with climb-controlled recovery and the strain hardening rate $\theta_{V} = -C(\sigma - \sigma_{V})^3$. Suitable switch functions $H_1$ and $H_2$ are defined to combine the model [12].

$$H_1(x) = \frac{1}{1 + e^{-2cx}}$$

(3.4)

and

$$H_2(x) = \frac{1}{1 + e^{-2mx}}$$

(3.5)

Therefore, the model can be combined as follows when it is in the $\theta - \sigma$ curve [12]:

$$\theta(\sigma) = \theta_{III} \left(1 - H_1(\sigma - \sigma_{V})\right) + \theta_{IV} H_1(\sigma - \sigma_{IV}) + \theta_{V} H_2(\sigma - \sigma_{V})$$

(3.6)

According to the experiment results, it is found that $\sigma_{V}$ changed with strain rate which in the means of Asymptotic equation. The function can be illustrated as follows:

$$\sigma_{V} = a_{V} \sigma_{0} - b_{V} \sigma \times c_{V}$$

(3.7)

where, $a_{V}$, $b_{V}$ and $c_{V}$ are corresponding constant.

The flow stress can be integrated according to the relationship of strain hardening rate and stress as follows:

$$\sigma = \int \theta d\varepsilon$$

(3.8)

Hence, the relationship of flow stress and strain is as follows:
\[ \sigma = \int \left[ (B_{III} - M_{III}) \sigma \left( 1 - \frac{1}{1 + e^{-2\alpha \varepsilon}} (\sigma - \sigma_{IV}) + (B_{IV} - M_{IV}) \sigma \right) \right] d\varepsilon \]  

(3.9)

The fitting is made on the strain hardening rate results under different strain rates, and the parameters are illustrated in Table 2.

| Parameters | \( B_{III} \) | \( M_{III} \) | \( c \) | \( m \) | \( B_{IV} \) | \( M_{IV} \) |
|------------|--------------|--------------|--------|--------|-------------|-------------|
| Value      | 3930.2       | 24.4         | 0.03   | 80.5   | -395.9      | -8.6        |
| Parameters | \( f \)      | \( a_{sr} \) | \( b_{sr} \) | \( c_{sr} \) | \( m \)     |
| Value      | 0.0026       | 233.6        | 295.6  | 0.99918| 0.03        |

The \( \theta - \sigma \) curve is illustrated in figure 5. It is found that the strain hardening rate decreases almost linearly when the strain rates are on the level of quasi-static (0.001/s and 1/s, respectively). However, the work hardening rate decreases firstly at the stage III, increases again during stage IV and decreases again to the end when the strain rates are in the range of 1000/s~5500/s.

According to the microstructure investigation by TEM, the material characterizes with precipitation of S phase (Al\(_2\)CuMg) which has high strength than the matrix. Hence, the precipitate cannot be sheared under the quasi-static loading but will be sheared under the dynamic loading which will provide enough internal stress for the hard phase. In the first stage, the precipitates become the obstacles of dislocation which will contribute as the storage by means of geometrically necessary dislocations when the strain is small. During the second stage, the interaction of dislocation accumulation and annihilation/dynamic recovery is the main procedure because of the shear of precipitate under large strain and high strain rate. The method of Cheng et al.\(^{[13]}\) is referred to determine the series of parameters. The constitutive model is established finally according to the parameters obtained.

4. The formability evaluation based on the solid-liquid coupling modeling

The impact hydroforming characterizes with flexible liquid and impact loading which is an obvious process of solid-liquid coupling. Hence, the finite element modeling is an available and useful method to be used to investigate the IHF procedure. In the first section, what is discussed is the corresponding parameters of impact hydroforming and the models that used for the simulation.

4.1. Impact hydroforming principle and modeling configuration

The principle of the impact hydroforming is illustrated as follows: The projectile is accelerated by the energy source in the manner of pressured gas or compressed liquid; and then the liquid is stimulated by the moved projectile; finally, the blank is formed by the liquid with high pressure and velocity. The principle of this process and the crucial parameters are illustrated in figure 6. The deep drawing ratio is defined to describe the intensity of the deformation as follows:

\[ DR = \frac{D_t}{d_p} \]  

(4.1)

where, \( DR \) stands for deep drawing ratio, and the limit value (LDR) represents deep drawing ratio that the blank can be formed completely without the area of flange, \( D_t \) indicates the diameter of the initial blank, and the effective diameter of liquid \( d_p \) has the relationship with the wall thickness \( t_b \):

\[ d_p = D_t - 2 \cdot t_b \]  

(4.2)

On the other hand, another parameter is needed to distinguish the difficulty of the deformation under the same deep drawing ratios. Hence, the parameter of deep drawing height ratio is defined to describe the degree of the height of deep drawing as follows:

\[ DHR = \frac{h_f}{d_p} \]  

(4.3)
where, $DHR$ stands for the deep drawing height ratio, $h_f$ represents the distance between the upper surface of flange and the lowest point of the deformed cup. The ultimate value of this parameter is defined as the limit deep drawing height ratio which is abbreviated as $LDHR$. $DHR$ will be very useful when the forming process is conducted under the condition of uncomplete deep drawing.

![Figure 6](image6.png)

**Figure 6.** Principle of impact hydroforming and definition of the critical parameters.

As it is illustrated in figure 7, the model meshing is introduced for the solid-liquid coupling finite element modeling (SLC-FEM). The projectile and liquid are treated as solid part and the same element is used with the blank from the view of vertical projection. The mass of the projectile is 60 kg, while the diameter is 250 mm. The height of the liquid is 152 mm, the effective diameter is 48.5 mm and the vertical element size is 1.2mm. As for the blank, the eight-node hexahedron solid element is employed in the Fluid-Structure Interaction (FSI) model. Furthermore, three layers are selected to investigate the thick gradient of strain and stress and the vertical size is set as 0.4mm. The blank holder and the lower die are treated as rigid parts by using the four-node quadrilateral shell element. The radius of the die is set as 5 mm.

The simplified Johnson-Cook constitutive model is employed to describe the mechanical behavior of the sheet. The keywords “MAT_SIMPLIFIED_JOHNSON_COOK_ORTHOTROPIC_DAMAGE” is used to considered the damage of the material. Directional damage begins after a defined failure strain is reached in tension and continues to evolve until a tensile rupture strain is reached in either one of the two orthogonal directions [14]. Gruneisen equation of state is utilized to express the dynamic behavior of the liquid which can correctly describe the characteristic of the shock wave [5].

4.2. Solid-liquid coupling modeling and the results

The formability is investigated by figuring out the relationship between the impact energy and forming ratio, meanwhile, the deep drawing height ratio and deep drawing ratio as for IHF procedure. Therefore, series of blanks with different diameters are formed under different impact energies to make them be the situation of complete, uncomplete deep drawing and crack. All the parts used to establish the formability curve are listed as in figure 8. It is found that the blank can be completely formed if the deep drawing ratio is not more than 1.77. And the blank has the possibility to be completely formed when the energy in the suitable range, it also possessed the probability to crack if the energy is too high when the forming ratio is on the level of 1.95. In addition, the blank has not any possibility to be completely formed if the deep drawing ratios are in the range of 2.13 and 2.31. The formability curve is established according to the impact energies and deep drawing height ratio which will be discussed later [3].
Figure 8. Parts used for establishing the curve of formability evaluation [5].

Three different deformation areas are distinguished according to the condition of the parts as shown in figure 9. They are incomplete deep drawing area, complete deep drawing area and crack area. In the same time, it is found that the limit forming ratio is 1.99 at the intersection of the two boundaries of three areas and the relative energy is 2207.2 kJ/m$^2$. Before the limit value, the forming energy increases with the deep drawing ratio, and it decreases with exponential trend when the forming ratio is larger than limit value [5].

Figure 9. Formability evaluation curve describing the relationship of impact energy and deep drawing ratio.

Figure 10. Formability evaluation curve describing the relationship of deep drawing height ratio and drawing ratio.

Furthermore, as illustrated in figure 10, the formability curve is established to express the relationship of deep drawing height ratio and deep drawing ratio. It is found that the limit deep drawing height ratio is 1.04 when the limit forming ratio is just 1.99. Before the value of 1.04, the $DHR$ increases linearly with the $DR$, however it decreases exponentially after the limit value [5].

5. Conclusions
(1) The elongation increases obviously when the strain rates are in the level of 3000–5000/s and the material has a better ability to endure the local deformation after the necking point.
(2) The work hardening rate characterizes with decreasing linearly firstly, increasing secondly and then decreasing again with non-linear trend. A modified Kocks-Mecking model is used to describe the feature of the particular variation of flow stress.
(3) The formability can be evaluated by the means of Solid-Fluid Coupling FEM for impact hydroforming and the formability curves are established to evaluate the relationship between impact energies, the deep drawing height ratios and deep drawing ratios.

Acknowledgments
Authors wish to acknowledge the funding support from National Natural Science Foundation of China (No. 51875548), Natural Science Foundation of Liaoning Province of China (Grand No. 20180550851),
Project for transfer and transformation of scientific and technological achievements, Chinese Academy of Sciences, Henan Province (No. 2020204).

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