The mechanical properties of high strength Al alloy sheet under quasi-static-dynamic loading

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Abstract. To investigate the mechanical properties of high strength Al alloy, the AA2024 was selected and conducted the uniaxial tensile tests at room temperature under different loading modes, namely pure quasi-static (QSD) loading mode, pure dynamic loading mode and quasi-static-dynamic loading mode. The mechanical properties such as yield stress (YS), ultimate tensile stress (UTS), total elongation and strain rate sensitivity were compared. The results shown that the UTS under QSD loading mode is larger than that of quasi-static and pure dynamic loading mode, and dependent on prestrain levels. However, the YS at pure dynamic loading mode is less than that of QSD loading mode at prestrain of 10% but larger than that of prestrain of 6%. In addition, the QSD loading mode would further improve the total elongation of AA2024 compared to the elongation enhancement under pure dynamic loading mode. Finally, the variation of strain rate sensitivity under different loading modes was analyzed to explain the evolution of tensile properties of AA2024.

1. Introduction
As a high strength aluminium alloy belongs to Al-Cu, the AA2024 alloy possessed outstanding comprehensive properties, such as high specific strength, high fracture ductile, low density and good heat resistance compared to other commercial Al alloys. Hence, it has been widely used in aerospace field recently to manufacture the airplane parts like skins, ribs and pillar, frames and so on. However, with the development of design concept of airplane’s structures, in aspect of complex thin-walled integrate sheet components especially the part with large deformation, its manufacturing characteristics has been exceeded the forming limits of AA2024 under the traditional cold forming technology.

To overcome the issues aforementioned, some technologies such as creep aging forming (CAF) [1], explosive forming (EF) [2], electromagnetic forming (EMF) [3] etc. have been developed recent years, which based on the characteristics of material’s sensitivity to strain rate. In addition, Zhang [4] proposed an impact hydroforming technology to manufacture the frame parts of airplane by two forming passes that was preforming (hydroforming under quasi-static loading mode) and final forming (impact hydroforming under dynamic loading mode). Indeed, the whole forming process was similar to quasi-static-dynamic (QSD) loading mode. It has been approved that the QSD loading mode could dramatically improve the formability of some materials. Liu [5-7] studied the QSD formability of AA5052-O by uniaxial and plane-strain tension experiments. It was found that nearly two-fold increase in limit strain of plane-strain state compare to quasi-static loading mode. Li [8] pointed out that the total...
tension strain under QSD loading mode of AA5182 would be the superposition between quasi-static strain and pure dynamic strain limitation. In addition, Lee [8-10] systematically investigated the mechanical behavior and the mechanism of formability improvement of 304L under QSD loading mode. However, since the difference of chemical composition, these results cannot representative the properties of 2xxx series aluminium alloys.

Accordingly, this study aims at investigating the influence of different loading modes namely quasi-static, pure dynamic and QSD loading mode on AA2024 through uniaxial tensile tests at room temperature, to compare the mechanical properties such as yield stress (YS), ultimate stress (UTS), total elongation and strain rate sensitivity. In current study, AA2024 was selected as a representative because of its widely applications in aerospace field.

2. Material and experiments

2.1. Material
The material used in current study was rolled sheet Al-Cu alloy AA2024 (O state: annealing heat treatment) with 1.2mm thick.

2.2. Experimental procedure
Although it would be perfect way to evaluate the deformation behaviours of material under a wide range of strain rate using the same testing machine, it is impractical because of the restricted range of velocity of quasi-static tensile tests machine. Thus, in current study, a 10kN Instron tension machine (Figure 1(a)) was used to perform the uniaxial tensile tests under quasi-static condition, while dynamic loading was conducted in split Hopkinson tensile bar (SHTB) (Figure 1(b)). Besides, the strain rate was affected by the dimension of specimens, to obtain the very high strain rate, the method of controlling and reducing the dimension of specimen was used. Therefore, dog-bone specimens with the gauge length and initial width of 5mm were cut from the as-received sheet with length direction parallel to the rolling direction (RD) of the sheet as depicted in Figure 1(c). In addition, The SHTB system used in current study included striker bar (projectile), incident bar and transmitter bar that made by steel with diameter of 20mm, in addition, as well as strain gauge, an oscilloscope, and data processing system. During the test, the specimens were put and fixed between the incident and transmitter bar with a special clamp apparatus. After that, the projectile was driven by the high pressure N2 gas and impacted incident bar instantly. Thus, the specimen was deformed by the occurrence of elastic waves within very short time. The signals were captured by the strain gauges and displayed on the oscilloscope screen. Assumption the elastic waves was just transmitted along the length direction of bars, thus, the mean strain, mean stress and instant strain rate was obtained from the signals based on one dimensional wave theory. The details equations are shown as follow:

\[ \varepsilon(t) = -\frac{2C}{l_0}\int_0^t \varepsilon_R(t)dt \]  
\[ \sigma(t) = E\frac{A}{A_0}\varepsilon_T(t) \]  
\[ \dot{\varepsilon}(t) = -\frac{2C}{l_0}\dot{\varepsilon_R}(t) \]

Where \( \varepsilon(t) \), \( \sigma(t) \) and \( \dot{\varepsilon}(t) \) are the mean strain, mean stress and instant strain rate respectively, \( \varepsilon_R(t) \) and \( \varepsilon_T(t) \) are the reflected strain wave and transmitted strain wave respectively, C is the velocity of elastic wave in the steel bars, \( l_0 \) is the gauge length of specimen, E is the Young’s modulus of the bar’s material, A and \( A_0 \) are the cross section areas of bars and the initial specimen respectively, t is the deformation time.
To compare the mechanical properties under different loading modes, the uniaxial tensile tests were conducted at room temperature with the strain rate of 0.001\(s^{-1}\) and 1000\(s^{-1}\)~5000\(s^{-1}\) corresponding to quasi-static loading mode and pure dynamic loading mode respectively. As for QSD loading mode, the prestrain levels (6\% and 10\%) were stretched under quasi-static loading mode with a constant strain rate of 0.001\(s^{-1}\), subsequently, dynamic loading was carried out with the range of strain rate of 1000\(s^{-1}\)~5000\(s^{-1}\). As summarized in table 1.

Table 1. Uniaxial tensile tests matrix; ( √ ) means that the test was accomplished at these condition

| Strain rate (s\(^{-1}\)) | Loading mode          | Quasi-static | Pure dynamic | QSD 6\% | QSD 10\% |
|--------------------------|------------------------|--------------|--------------|----------|----------|
| 0.001                    | √                      |              |              | √        | √        |
| 1000~5000                | ---                    | √            |              | √        | √        |

3. Results and discussion

3.1. effect of loading modes on YS and UTS of AA2024

Figure 2 (a) shows the YS and UTS under quasi-static, pure dynamic and QSD loading mode. It is worth to notable that the stress value produced 0.2\% residual deformation was specified as YS deriving from the stress strain curve. Strain rate has a dramatically influence on YS and UTS of AA2024 alloy. As depicted in Figure 1(a), while strain rate increase, the YS slightly increase till strain rate of 2500\(s^{-1}\) and sharply increase at strain rate beyond 2500\(s^{-1}\) to 4500\(s^{-1}\) and drop after 4500\(s^{-1}\). The variation of UTS is same to that of YS except the slightly decrease before 2500s\(^{-1}\). For QSD loading mode, the YS and UTS increase at strain rate beyond 1000\(s^{-1}\) to 2500\(s^{-1}\), and then, the YS decrease while the UTS continue increase after strain rate of 2500\(s^{-1}\). Furthermore, to investigate the effect of prestrain levels on the flow stress of AA2024, the variation of YS and UTS were studied at the similar strain rate level (from 2000\(s^{-1}\) to 3000\(s^{-1}\)). It can conclude that the YS and UTS increase with prestrain increase.

3.2. effect of loading modes on total elongation of AA2024

Figure 2 (b) shows the total elongation under quasi-static, pure dynamic and QSD loading mode. The total elongation increases at the range of strain rate from 0.001\(s^{-1}\) to 4500\(s^{-1}\) and dramatically drop after strain rate of 4500\(s^{-1}\). Thus, the strain rate of 4500\(s^{-1}\) is the threshold for plasticity improvement of AA2024. For QSD loading mode, the total elongation increases with strain rate increase. In addition, at the similar strain rate level (from 2000\(s^{-1}\) to 3000\(s^{-1}\)), the QSD loading mode can further improve the total elongation of AA2024 compare to quasi-static and pure dynamic loading mode. Moreover, at the
strain rate of 2000s\(^{-1}\)~2500s\(^{-1}\), the total elongation under the prestrain of 6% was larger than that of 10%, but the results alter to contrast while strain rate beyond 2500s\(^{-1}\) to 3000s\(^{-1}\). Hence, it is vital for AA2024 to determine the strain rate and prestrain levels when forming complex parts with two passes forming process.

3.3. effect of loading modes on strain rate sensitivity of AA2024

Usually, the flow stress variation is a function of strain and strain rate at room temperature. And the strain rate sensitivity is expressed by a differential function of stress and strain rate at selected plastic strain as shown by the following equation.

\[
m = \frac{\partial \ln \sigma}{\partial \ln \dot{\varepsilon}}
\]  

Figure 3. The variation of strain rate sensitivity at different specific plastic strain under different loading mode; (a) quasi-static and pure dynamic loading mode; (b) QSD loading mode at different prestrain levels

In current study, at the selected plastic strain (\(\varepsilon = 0.1, 0.2, 0.3\) and 0.4), the strain rate sensitivity \(m\) was calculated by fitting the \(\ln \varepsilon - \ln \sigma\) curve. Figure 3 (a), (b) shows the variation of strain rate sensitivity at different specific plastic strain under different loading mode. It can be concluded that the AA2024 has a high sensitivity to strain rate no matter under quasi-static and pure dynamic loading mode or QSD loading mode. Furthermore, for quasi-static and pure dynamic loading mode, the values of \(m\) are nearly -0.128~0.384 at strain rate from 0.001s\(^{-1}\) to 4927s\(^{-1}\). With the increase of plastic strain, the strain rate sensitivity \(m\) decreases at different strain rate except for the strain rate at the range from 2673s\(^{-1}\) to 2963s\(^{-1}\). In addition, at strain rate beyond 4622s\(^{-1}\) to 4927s\(^{-1}\), the values of \(m\) change from positive to negative with the plastic strain increasing which means the flow stress decrease, this phenomenon agrees well with the variation of UTS as depicted in Figure 2(a). On the other hand, at the plastic strain \(\varepsilon = 0.1\), while the strain rate increase, the values of \(m\) increase till strain rate of 4622s\(^{-1}\) and drop at strain rate from 4622s\(^{-1}\) to 4927s\(^{-1}\). This explain that the total elongation dramatically increases at strain rate from 3000s\(^{-1}\) to 4500s\(^{-1}\) and drop after strain rate of 4500s\(^{-1}\). For QSD loading mode, the values of \(m\) are nearly -0.143 to 0.282 at strain rate from 1146s\(^{-1}\) to 4639s\(^{-1}\) under different prestrain levels. And with the strain rate increase, the values of \(m\) increase and not dependent on the prestrain levels. But it is worth to notable that the values of \(m\) almost turn to negative at strain rate from
2306s\(^{-1}\) to 4639s\(^{-1}\), which means the softening happened at this range of strain rate after pre-deformed. In addition, at the similar strain rate levels (from 2000s\(^{-1}\) to 3000s\(^{-1}\)) and \(\varepsilon = 0.1\), the value of \(m\) is negative at prestrain of 6% while positive at 10%, thus, the UTS at prestrain of 10% is larger than that of 6%.

4. Conclusions
The effect of loading modes on the mechanical properties of AA2024 have been investigated and the following conclusion can be drawn:

- Under different loading modes (quasi-static, pure dynamic and QSD) at a similar strain levels (from 2000s\(^{-1}\) to 3000s\(^{-1}\)), the UTS under QSD loading mode is larger than that of quasi-static and pure dynamic loading mode. Furthermore, the UTS increases with the prestrain levels increase. However, the YS at pure dynamic loading mode is less than that of QSD loading mode at prestrain of 10% but larger than that of prestrain of 6%.
- Strain rate has a significant on the total elongation of AA2024, compare to quasi-static loading mode, the total elongation under pure dynamic loading mode would dramatically improve with strain rate increasing, but existing a threshold at strain rate of 4500s\(^{-1}\). And the QSD loading mode would further improve the total elongation compare to pure dynamic loading mode. In addition, the prestrain levels have influence on improvement of total elongation.
- The variation of strain rate sensitivity under different loading modes agree well with the variation of UTS and total elongation. Moreover, the values of \(m\) show negative at specific condition which means softening happened.

5. References
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