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# Prediction of ductile fracture initiation for powder metallurgical aluminum-copper preforms using FEM

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## Abstract

**Background:** The deformation of Al-Cu alloys is limited to an intermediate stage due to formation of ductile fracture. The present paper deals with the investigation of the effect of process parameters on the strain paths and ductile fracture initiation of powder metallurgical (P/M) aluminum-copper preforms using FEM during metal forming.

**Methods:** The various Al-Cu preforms were prepared using P/M route. Ductile fracture criterion based on local compressive and tensile strains in combination with FEM was employed to determine the fracture limit.

**Results:** The fracture loci were determined by using experimental method for P/M Al, Al-2wt%Cu, Al-4wt%Cu and Al-6wt%Cu preforms. The results were analyzed for the influence of material composition, initial relative density, aspect ratio and friction on the ductile fracture initiation. The FEM simulations provided detail information on the local compressive and tensile strain paths.

**Conclusions:** The results demonstrate that increase of copper content has decreased the plain ductility limit of the material and, hence the fracture limit decreases. In addition, the fracture limit increases with increase in the initial relative density and aspect ratio or decrease in the tool-work piece interface friction irrespective of the material composition.

**Keywords:** Powder metallurgical preform; Ductile fracture initiation; Finite element method

## Background

Powder metallurgy (P/M) technique is being used to produce parts with superior properties, namely, high strength, wear resistant, close dimensional tolerances, and intricate and near-net shapes. It is rapid, economical, and high-volume production method of porous materials, composite materials, refractory materials, and special duty alloys to be used in aircraft, automotive, and other manufacturing industries (Rosochowski et al. 1998; Poshal and Ganesan 2010). Due to its optimal physical and mechanical properties, aluminum-copper composites have been widely applied in automobile and aerospace industries. However, making products with insufficient information on the effect of various processing conditions on ductile fracture leads to an extensive surface and edge cracking. Therefore, it is essential to study the fracture behavior of P/M aluminum-copper preforms under various processing conditions, namely, material composition, geometry, initial relative density, and friction, and hence, engineers and technicians can make an early modification of the production processes to avoid the risk of failure of material.

In the past, many fracture criteria have been developed to predict the fracture limit. Lee and Kuhn (1973) developed a mathematical model based on total strain at failure to evaluate the effect of material characteristics and process parameters on the initiation of ductile fracture. Zhang et al. (2000a) and Down and Kuhn (1975) investigated the fracture loci (tensile strain/compressive strain) for porous materials under various processing conditions. In addition, several authors (Vujovic and Shabaik 1986; Clift et al. 1990; Ko et al. 1996) developed models for predicting ductile fracture initiation during bulk metal forming. These criteria can be categorized as empirical and semi-empirical criteria. The empirical criteria are either strain based at fracture locus or stress based defined in terms of stress formability index (Xue-min et al. 2009).

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Criteria based on cumulative plastic energy and void coalescence can be considered as semi-empirical criteria.

Many authors (Yu et al. 2007; Xingquan et al. 1997; Xingquan et al. 1998) applied strain-based ductile criterion to predict the ductile fracture limit using finite element method (FEM) during plastic deformation. They revealed the existence of a linear relation between the tensile strain and compression strain at failure for a given processing conditions. In the current work, the criteria performed by Lee and Kuhn (1973, 1984), Kuhn et al. (1973), and Shah and Kuhn (1986) have been used in the determination of the fracture limit in terms of local tensile and compressive strains.

The criterion is expressed as:

$$\varepsilon_{\theta c} = a - \frac{1}{2}\varepsilon_{zc} \tag{1}$$

where subscript c represents the value at cracking, the intercept, a, is the material constant, and $\varepsilon_\theta$ and $\varepsilon_z$ are the tensile and compressive strains, respectively.

The aim of the present study was to predict the initiation of ductile fracture for P/M aluminum-copper preforms under various processing conditions. For this purpose, cold upsetting and ring compression tests were conducted to develop the actual material properties under different processing conditions.

## Methods

### Experimental procedures

Aluminum-copper preforms were prepared by using P/M route from atomized pure aluminum and copper powders of each −325 μm mesh size. The purity level of aluminum powder is 99 % with a maximum of 0.53 % insoluble impurity limit while copper powder is 99 % pure, and it has a maximum of 0.5 and 0.03 % impurities of iron and heavy metal (Pb), respectively. Aluminum-copper compacts with copper content ranging from (0–6 wt.%) of various initial relative densities were made by applying recommended compaction pressures. Zinc stearate was used to lubricate the die, punch, and butt to reduce interface friction. The powder compacts were sintered in a tubular furnace at a temperature of 550 ± 10 °C for a holding time of 45 min. The sintered preforms were allowed to cool to room temperature inside the furnace by switching off the power source of the furnace. The density of the preform was ascertained by using Archimedes's principle at room temperature with an accuracy of ±1 %.

Sintered pure Al, Al-2 wt.%Cu, Al-4 wt.%Cu, and Al-6 wt.%Cu preforms with different initial relative density, 80, 85 and 90 % and aspect ratio (height/diameter) of 0.83, were compressed between two parallel platens on a hydraulic press of 50 ton capacity. Each specimen was subjective to incremental loading until the appearance of the first visible crack on the surface of the specimen. To determine the coefficient of friction, standard ring compression specimens of outer diameter: inner diameter: height ratio of 6:3:2 (20:10:6.67) were prepared by machining the sintered specimens. Both sides of the specimen were polished using emery paper to ensure the same surface roughness.

### Finite element (FE) simulation

The FE modeling of the compression test was carried out using commercial FEM software (DEFORM 2D). An axisymmetric formulation of the billet was considered to save computation time, and hence, the 2D modeling represents only a quarter of the specimen. Quadrilateral nodded 2000 elements with size ratio of 3 were chosen to mesh the billet. The specimen was considered as a porous material with initial relative density of 80, 85 and 90 % and was given as input for the simulation. Further, the FE simulation was used to derive the friction calibration curves to determine the coefficient of friction. Fig. 1a, b shows the FE modeling of P/M aluminum-copper preforms before and after deformation, respectively.

## Results and discussions

### Compression tests

Series of compression tests were carried out to determine the flow stress equation of P/M aluminum-copper preforms under various processing conditions. For this purpose, the Hollomon flow stress equation (Staley and Campbell 2000) was taken as:

$$\sigma = K\in^n \tag{2}$$

where $K$ is the strength coefficient, $n$ is the strain hardening exponent, $\sigma$ and $\varepsilon$ are the effective stress and effective strain, respectively.

The results in Table 1 show an increase in the strain hardening exponent, $n$, with decrease in the initial relative density or increase in the copper content in the aluminum matrix of the composite. This is due to the influence of more number of inherent porosity in lower density preforms that leads to more yielding of metals during deformation. On other hand, the strength coefficient, $K$, increases with increase in the copper content or increase in the initial relative density.

The friction factor, $m$, used in the FE simulation was determined using ring compression test. Fig. 2a, d presents the friction calibration curves for P/M pure Al, Al-2 wt.%Cu, Al-4 wt.%Cu, and Al-6 wt.%Cu preforms with various initial relative densities.

The summarized friction factor values are presented in Table 2.

Based on the developed material properties ($n$ and $K$) and interface friction factor ($m$), FE simulation was conducted, and a comparison between experimental and FEM-obtained deformation load requirements was performed for validation of experimental work. Fig. 3a, d shows the

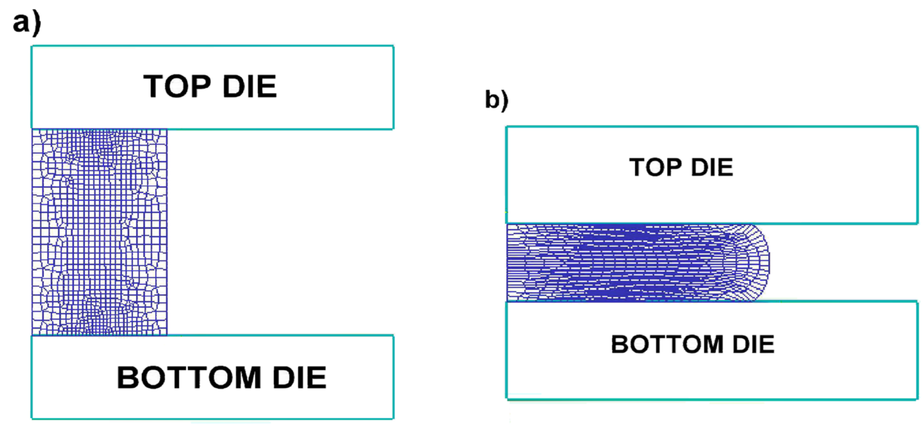


**Fig. 1** FE modeling of P/M preform **a** before deformation and **b** after deformation

comparison between experimental and FEM-obtained deformation load for compression of P/M aluminum, Al-2 wt.%Cu, Al-4 wt.%Cu, and Al-6 wt.%Cu preforms with initial relative density of 90 % at 50 % height reduction, respectively. The maximum absolute error between experimental and FEM load requirement is less than 5 % which validates the experimental results.

### Determination of fracture loci

Critical fracture strain of P/M aluminum-copper preforms was evaluated based upon the local compressive and tensile strains. As it was reported by Chitkara and Liaghat (2001) that two sets of grid lines were applied by inscribing fine lines on the equatorial region of the specimen which were then compressed incrementally until the appearance of the first visible cracks on the surface of the specimen. Thus, local compressive strain, $\ln(s/s_o)$, and tensile strain, $\ln(w/w_o)$, were determined by taking measurements of grid lines during compression. The strain value obtained from the measurement of the local grid lines are identical to that of measured from the overall diameter of the specimen ($\ln(D/D_o)$). Therefore, the latter was used in the determination of the tensile strain. The value of the intercept, $a$, in Equation 1 represents the plain strain ductility of the material (Chitkara and Liaghat 2001), and it was determined for different processing conditions. Table 3 presents the values of intercept, plain ductility limit, for P/M Al, Al-2 wt.%Cu, Al-4 wt.%Cu, and Al-6 wt.%Cu preforms with different initial relative densities.

It is clearly observed that the values of the intercept, $a$, decreases with increase in the initial relative density. This indicates that as the number of pores increase in the sintered preforms, the plain ductility limit of the material decreases. Bourcier et al. (1986) revealed that the presence of pores acts to concentrate the strain in their vicinity and, as a result, the macroscopic ductility and flow stress decrease which lead to fracture of the material. A decrease in the plain ductility limit was observed with an increase in the copper content of the preforms.

### Effect of copper content on ductile fracture initiation

The effect of copper content on ductile fracture initiation was evaluated using DEFORM 2D software in combination with strain-based ductile fracture criterion. The material properties, $n$, $K$, and $m$ which were obtained using experimental method, were employed as input for the simulation. Fig. 4 shows the effect of copper content on the strain path and ductile fracture initiation for Al, Al-2 wt.%Cu, Al-4 wt.%Cu, and Al-6 wt.%Cu preforms with 90 % initial relative densities.

From Fig. 4, it can be seen that the intersection point decreases with increase of the copper content in the composite. This shows that preforms with more copper content in the matrix undergo relatively early ductile fracture.

**Table 1** The values of $K$ and $n$ for P/M pure Al, Al-2 wt.%Cu, Al-4 wt.%Cu, and Al-6 wt.%Cu preforms with initial relative densities of 80, 85 and 90 %

| Material | Strain hardening exponent, $n$ | | | Strength coefficient, $K$ | | |
|---|---|---|---|---|---|---|
| | IRD = 80 % | IRD = 85 % | IRD = 90 % | IRD = 80 % | IRD = 85 % | IRD = 90 % |
| Al | 0.32 | 0.31 | 0.28 | 244.23 | 249.14 | 261.91 |
| Al-2 wt.% Cu | 0.49 | 0.44 | 0.41 | 296.49 | 313.88 | 366.14 |
| Al-4 wt.% Cu | 0.51 | 0.45 | 0.42 | 327.99 | 345.16 | 381.46 |
| Al-6 wt.% Cu | 0.51 | 0.46 | 0.43 | 347.93 | 362.50 | 399.18 |

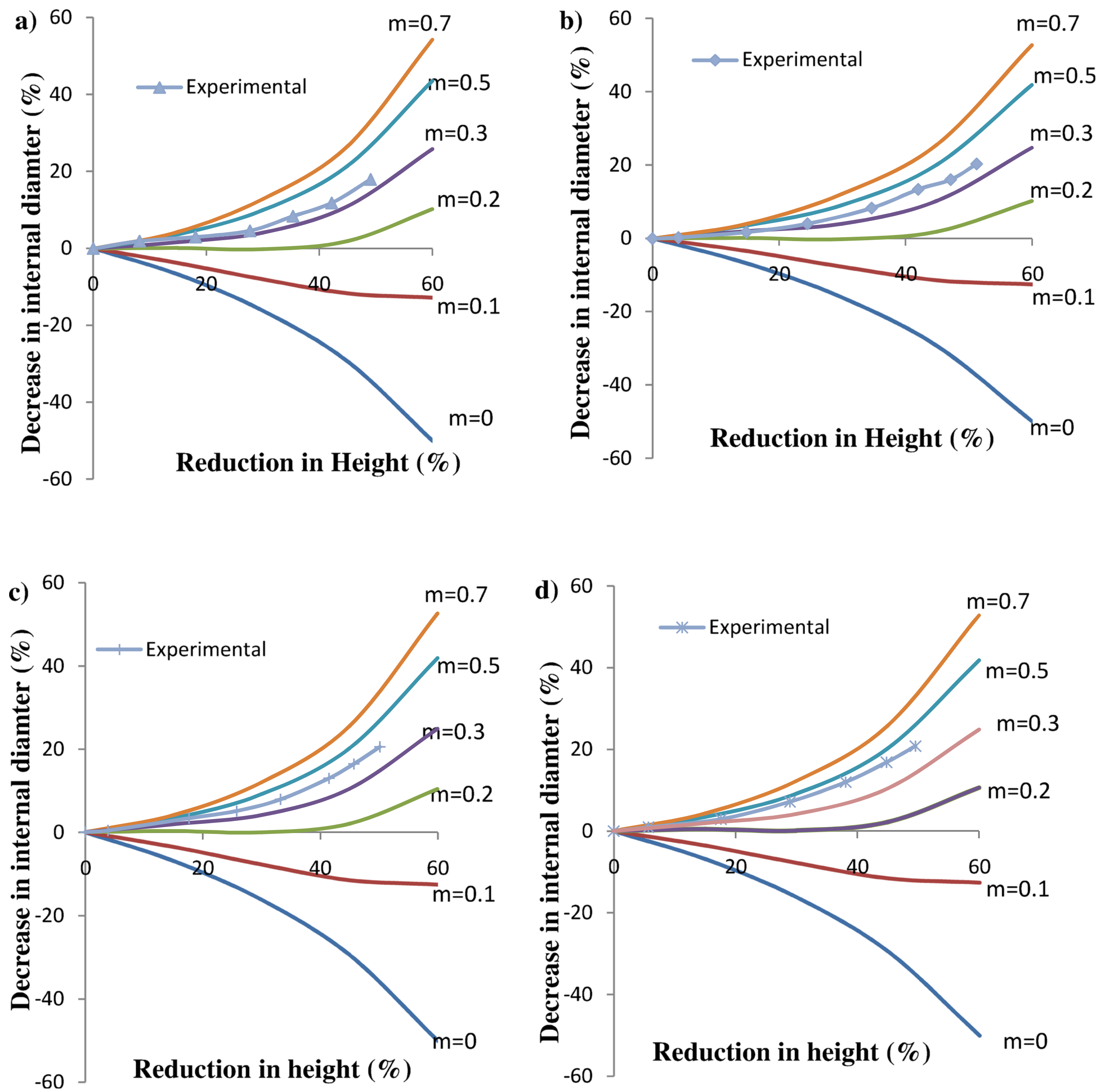


**Fig. 2** Friction calibration curve for P/M **a** Al preforms, **b** Al-2 wt.% Cu preforms, **c** Al-4 wt.% Cu preforms, and **d** Al-6 wt.% Cu preforms with 90 % initial relative density

**Table 2** Friction factor, *m*, for Al, Al-2 wt.% Cu, Al-4 wt.% Cu, and Al-6 wt.% Cu preforms with initial relative densities of 80, 85 and 90 %

| Material | Friction factor, *m* | | |
|---|---|---|---|
| | IRD = 80 % | IRD = 85 % | IRD = 90 % |
| Al | 0.72 | 0.53 | 0.34 |
| Al-2 wt.% Cu | 0.78 | 0.54 | 0.37 |
| Al-4 wt.% Cu | 0.80 | 0.55 | 0.39 |
| Al-6 wt.% Cu | 0.82 | 0.57 | 0.41 |

This is due to increased formation of second phase particles in the aluminum matrix which is brittle by nature, and hence, the material is prone to early ductile fracture initiation and lower formability.

### Effect of initial relative density on ductile fracture initiation

P/M aluminum-copper preforms with three different initial relative densities, 80, 85, and 90 %, were selected for the simulation of the effect on ductile fracture initiation. Fig. 5a, c shows the effect of initial relative density on

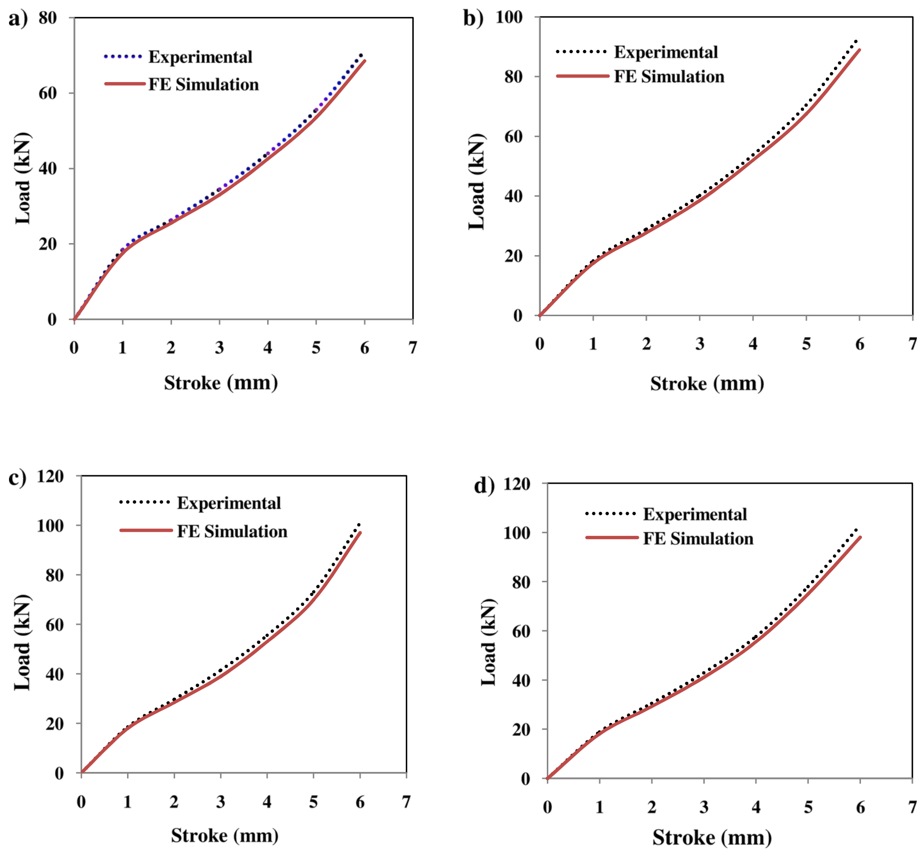


**Fig. 3** Experimental and FEM load requirement for compression of P/M **a** Al, **b** Al-2 wt.% Cu, **c** Al-4 wt.% Cu, and **d** Al-6 wt.% Cu with initial relative density of 90 % at 50 % height reduction

strain path and ductile fracture initiation of P/M Al, Al-2 wt.% Cu, Al-4 wt.% Cu, and Al-6 wt.% Cu preforms.

It is understood from Fig. 5 that the ductile fracture limit increases with an increase in the initial relative density irrespective of the copper content in the material. It is believed that more number of pores in the lower initial relative density preforms lead to nucleation and linkup of voids or cavities at the second phase particle which latter resulting in the initiation of ductile fracture of the material (Bourcier et al. 1986). An increase in the porosity decreases the plain ductility, and hence, the fracture limit is reduced.

**Table 3** Plain ductility limit of P/M Al, Al-2 wt.% Cu, Al-4 wt.% Cu, and Al-6 wt.% Cu preforms with initial relative density of 80, 85, and 90 %

| Material | Intercept, *a* | | |
|---|---|---|---|
| | IRD = 80 % | IRD = 85 % | IRD = 90 % |
| Al | 0.121 | 0.201 | 0.321 |
| Al-2 wt.% Cu | 0.101 | 0.189 | 0.298 |
| Al-4 wt.% Cu | 0.098 | 0.172 | 0.287 |
| Al-6 wt.% Cu | 0.083 | 0.142 | 0.241 |

## Effect of friction

Friction has a significant influence on the formability of materials during plastic deformation. Particularly, P/M components exhibits sever frictional conditions during bulk metal forming due to the presence of inherent porosity left after sintering (Venugopal et al. 1988). Thus, it is essential to evaluate the effect of friction on the strain paths and ductile fracture initiation. Friction factor values, 0.1, 0.3, 0.4, 0.5, 0.6, and 0.7, were selected for FE simulation. Fig. 6a, d presents the effect of friction on the strain path and ductile fracture initiation of P/M Al, Al-2 wt.% Cu, Al-4 wt.% Cu, and Al-6 wt.% Cu preforms with initial relative density of 90 %, respectively.

It is clear that increase in friction factor results in early initiation of ductile fracture irrespective of the copper content in the preforms. The result agrees well with the findings of authors (Lee and Kuhn 1973; Zhang et al. 2000a; Zhang et al. 2000b). The barreling effect increases with increase in the tool-work piece interface friction

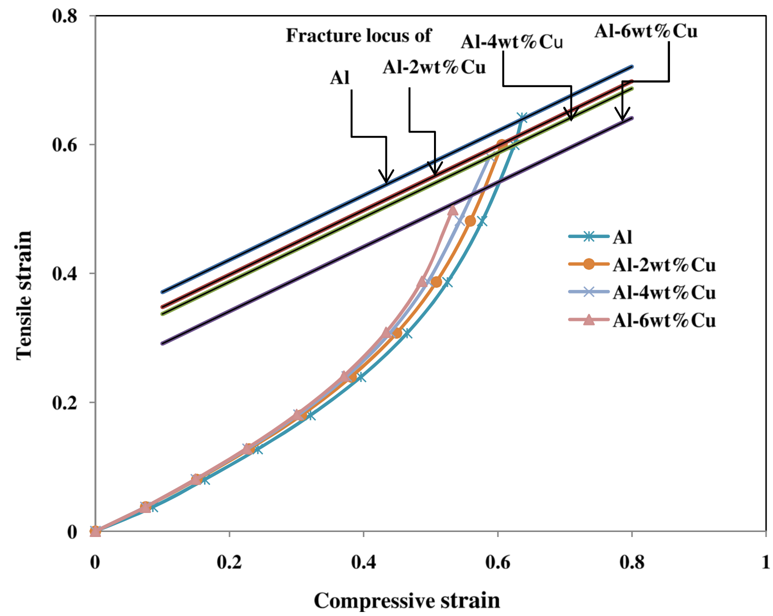


**Fig. 4** Effect of copper content on the strain path and ductile fracture initiation for P/M Al, Al-2 wt.% Cu, Al-4 wt.% Cu, and Al-6 wt.% Cu with initial relative density of 90 %

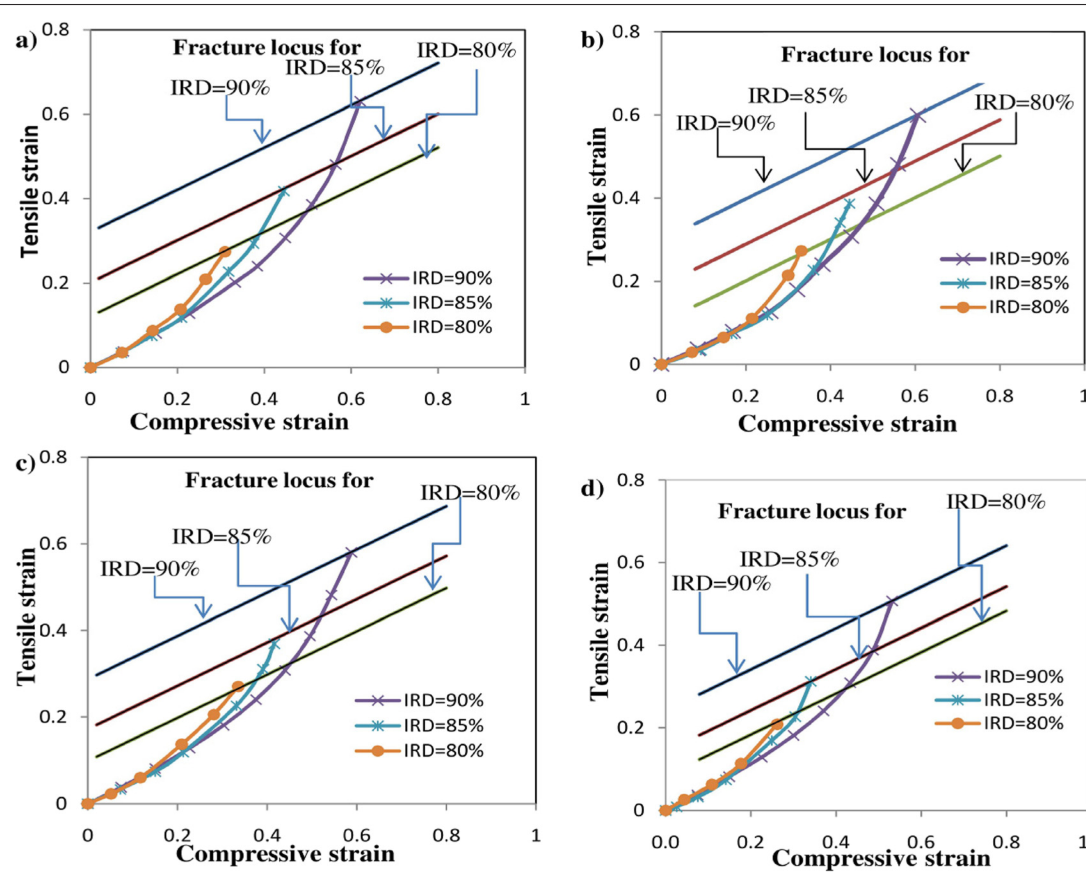


**Fig. 5** Effect of initial relative density on strain path and ductile fracture initiation for P/M **a** Al, **b** Al-2 wt.% Cu, **c** Al-4 wt.% Cu, and **d** Al-6 wt.% Cu preforms

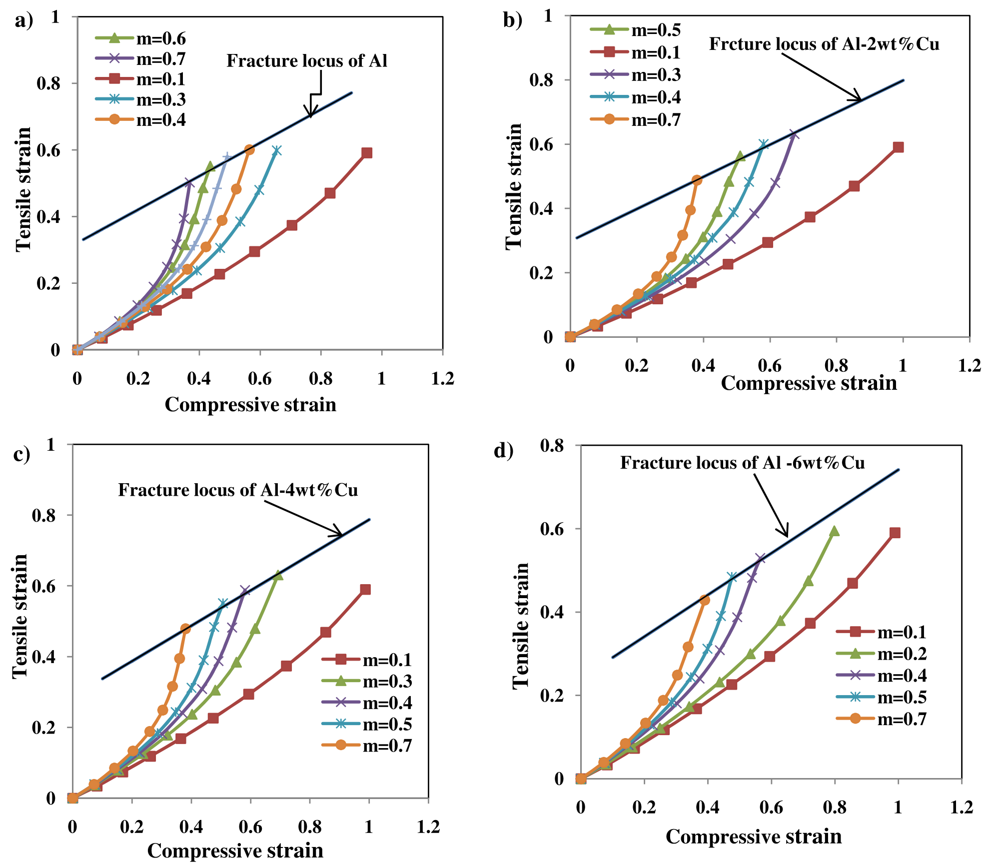


**Fig. 6** Effect of friction on strain path and ductile fracture initiation of P/M **a** Al, **b** Al-2 wt.% Cu, **c** Al-4 wt.% Cu, and **d** Al-6 wt.% Cu preforms with 90 % initial relative density, respectively

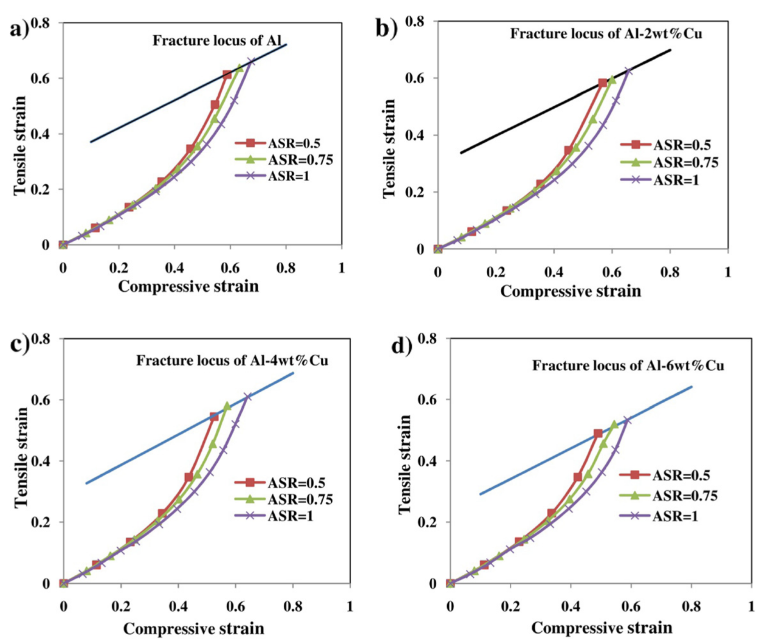


**Fig. 7** Effect of aspect ratio on strain path and ductile fracture initiation for P/M **a** Al, **b** Al-2 wt.% Cu, **c** Al-4 wt.% Cu, and **d** Al-6 wt.% Cu preforms with 90 % initial relative density, respectively

which is due to restricted flow of metals at the interfaces. More metal flows to the equatorial region of the specimen which leads to surface crack formation.

### Effect of aspect ratio

Fig. 7a, d shows that the effect of preform aspect ratio on the strain path and ductile fracture initiation. It indicates that aspect ratio has an obvious effect on the ductile fracture limit. Increase in aspect ratio has increased the fracture initiation limit irrespective of the copper content in the preforms.

The higher aspect ratio yields a higher ductile fracture initiation limit as the increases of volume of material increases the mobility of particles which subsequently increases the stress and strain to fracture, and the same is revealed elsewhere (Ananthanarayanan 2010). In addition, it is believed that for higher aspect ratio preforms, the amount of contact pressure towards the center of interface between tool and work piece is small which leads to reduced dead metal zone formation, and hence, the job platen friction is low. As a result, the flow metal at the tool-work piece interface is relatively less restricted and the preform exhibits reduced barreling phenomena. Therefore, preforms with higher aspect ratio undergo better ductile fracture limit and formability.

## Conclusions

The research investigates the effect of process parameters on the strain path and ductile fracture initiation of P/M aluminum-copper preforms during metal forming. For this purpose, the material properties, $n$, $m$, and $K$, were determined by experimental method. Finite element simulation in combination with Lee-Kuhn's fracture criterion was employed to evaluate the fracture limit for various processing conditions. The effect of process parameters, namely, copper content in the preform, initial relative density, aspect ratio, and interface friction on the ductile fracture initiation, was investigated. Increase in the copper content decreases the plain ductility limit, and hence, fracture limit decreases. The results revealed that increase in initial relative density and aspect ratio or decrease in the friction improved the fracture limit. The research findings can help researchers and industries to develop robust, reliable, and knowledge base process for secondary processing of P/M parts and select suitable process parameters to avoid the occurrence of fracture of parts.

#### Competing interests
The authors declare that they have no competing interests.

#### Authors' contributions
DWW carried out reviewing of literature, specimen preparation using P/M technique, mechanical testing and FEM simulations. MJD & AKK guided the entire research work successfully beginning from the research noble idea & made vital discussions thoroughly. All the authors have read and approved the manuscript.

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