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Original

Equivalent strain at large shear deformation: Theoretical, numerical and finite element analysis

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Abstract

In this study, effective strain is evaluated for large simple/pure shear deformations and new expressions are derived. The validity of these relations was checked by numerical calculations. In addition, finite element analysis of simple shear and pure shear modes of deformation was conducted using ABAQUS software. Additionally, two other major expressions for evaluating effective strain at large simple shear deformation were investigated and compared with finite element results. Based on FEM results, the linear relation between shear strain and effective strain large strains shall be replaced with the logarithmic one. It is also found that for the same amount of shear strain, a higher value of effective strain is accumulated in the material when it is deformed through simple shear rather than pure shear.

Keywords: Simple shear; Pure shear; Equivalent strain; Finite element analysis; Shear strain; Severe plastic deformation

1. Introduction

Simple shear and pure shear are considered as the most important modes in deformation of materials. While pure shear is an ideal deformation mode in metal forming operations (Segal, 1995), simple shear is considered as an optimal mode of deformation for grain refinement via severe plastic deformation (SPD) (Segal, 2002, 2006). Generally, most SPD techniques benefit from shear deformation of materials. In some techniques like equal channel angular pressing (ECAP) (Valiev & Langdon, 2006), high pressure torsion (HPT) (Zhilyaev & Langdon, 2008), twist extrusion (TE) (Beygelzimer, Varyukhin, Synkov, & Orlov, 2009) and simple shear extrusion (SSE) (Pardis & Ebrahimi, 2009), simple shear is a dominant mode of deformation while some other methods like pure shear extrusion (PSE) (Eivani, 2015) and accumulative channel-die compression bonding (ACCB) (Kamikawa & Furuhara, 2013) are based on pure shear deformation. In addition, in some other techniques such as cyclic extrusion-compression (CEC) (Richert & Richert, 1986) and cyclic expansion-extrusion (CEE) (Pardis, Chen, Ebrahimi, Toth, Gu, Beausir, & Kommel, 2015; Pardis, Chen, Shahbaz, Ebrahimi, & Toth, 2014; Pardis, Talebanpour, Ebrahimi, & Zomorodian, 2011) the two deformation modes (simple and pure shear) are both active. Since all of these SPD methods deal with giant straining of materials, the amount of accumulated equivalent strain can be considered as a suitable factor for comparing the degree of SPD imposed by these different techniques. Therefore, relations which convert shear strain to its equivalent effective strain are of great importance. This fact becomes even more important when considering the increasing interests on SPD processing of materials as well as development and modifications of various SPD techniques. However, fewer studies have been devoted to the basic relations between shear and equivalent strain values. In this study, these relations are reconsidered and investigated by finite element method (FEM). In addition, new expressions are presented for evaluation of effective strain at large shear deformation and their validity is examined by FEM. The results can be applied to estimate the accumulated strain after processing the samples by any specific forming/SPD technique. Before that, however,

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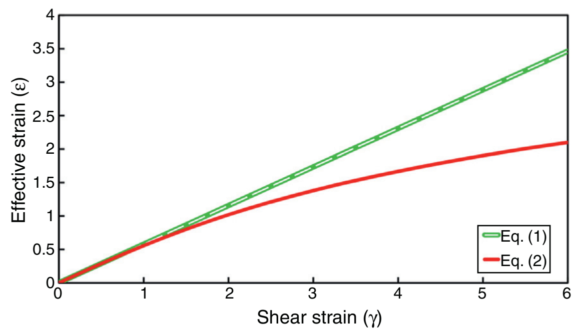

Fig. 1. Illustration of the equivalent strain as a function of shear strain calculated by Eqs. (1) and (2).

it is needed to determine the dominant deformation mode. In this regard, the kinematically admissible velocity field proposition for a given deformation process can make it much easier for considering simple shear/pure shear deformation modes in some techniques like Axi-symmetric forward spiral extrusion (Khoddam, Farhoumand, & Hodgson, 2011) and Vortex Extrusion (Shahbaz, Pardis, Ebrahimi, & Talebanpour, 2011; Shahbaz, Pardis, Kim, Ebrahimi, & Kim, 2016) where such classification might not be easily possible.

2. Effective strain at large shear strains

2.1. Simple shear

Generally, there are two main expressions for evaluating the equivalent strain at large simple shear deformation. Shrivastava, Jonas, and Canova (1982) suggested the following common equation for evaluating nominal equivalent strain at large simple shear deformation.

$$\bar{\varepsilon} = \frac{\gamma}{\sqrt{3}} \tag{1}$$

However, Polakowski and Ripling (1966) stated Eq. (1) would not be valid at large shear strains as the directions of the maximum normal stress and strain are not coincident in simple shear deformation and derived the following Eq. (2):

$$\bar{\varepsilon} = \frac{2}{\sqrt{3}} \ln\left[\frac{1}{2}\gamma + \sqrt{\left(1 + \frac{1}{4}\gamma^2\right)}\right] \tag{2}$$

This equation had been previously proposed by Eichinger (1955). Furthermore, there are records on a similar expression presented by Nadai (1937) for evaluating octahedral shear strain in simple shear deformation. However, the resulting values of these two major expressions would be significantly different at high shear strain values as illustrated in Figure 1.

According to Figure 1, these two equations are nearly coincident at relatively low shear strains ($\gamma < 2$). However, at higher shear strain values, the difference between the resulting equivalent strain values from these two relations becomes significant. Therefore, based on the increasing number of studies conducted on severe straining of materials by SPD, these relations should be reconsidered as the difference between them cannot be ignored.

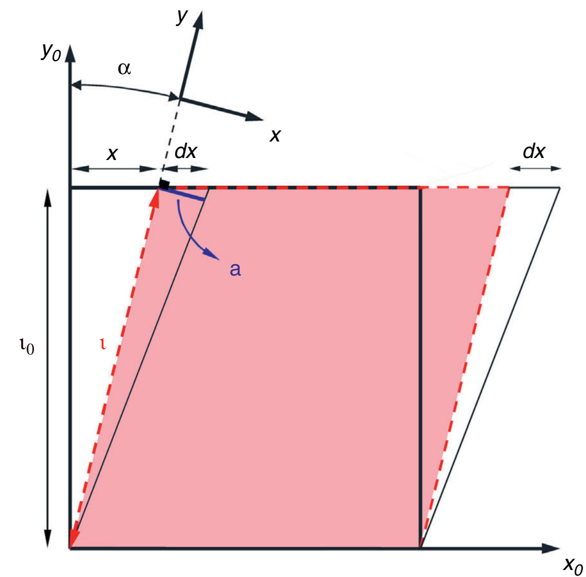

Fig. 2. Simple shear deformation of an elemental square into a parallelogram.

In our approach to evaluate equivalent strain for simple shear deformation, we consider a square of side length l_0 deformed by simple shear into a parallelogram (Fig. 2).

At this point, the amount of shear strain is defined by $\gamma = x/l_0$ which is based on the initial side length (l_0) and therefore, can be entitled as "engineering shear strain". However, it would not be correct to use this relation for any additional increments of shear deformation as the geometry has been changed to a parallelogram. Therefore, we introduce a new term (γ_t) called "True simple shear strain" which is based on the current geometry dimensions and is defined as follows:

$$d\gamma_t = \frac{a}{l} \cong \frac{dx \cos\alpha}{l} = \frac{l_0}{(l_0^2 + x^2)} dx \tag{3}$$

Integrating Eq. (3) yields:

$$\gamma_t = \int_0^x d\gamma_t = \int_0^x \frac{l_0}{(l_0^2 + x^2)} dx = \tan^{-1}\left(\frac{x}{l_0}\right) \tag{4}$$

Meanwhile, during simple shear deformation, an element of length (l_0) elongates to (l) and the corresponding strain components would be calculated as Eq. (5).

$$\varepsilon_y = -\varepsilon_x = \ln\left(\frac{l}{l_0}\right) = \ln\left(\frac{\sqrt{x^2 + l_0^2}}{l_0}\right), \quad \varepsilon_z = 0 \tag{5}$$

Considering simple shear deformation of a square of unit length ($l_0 = 1$), previous equations can be simplified to:

$$\gamma_t = \tan^{-1}\gamma \tag{6}$$

$$\varepsilon_y = -\varepsilon_x = \ln(\sqrt{\gamma^2 + 1}), \quad \varepsilon_z = 0 \tag{7}$$

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