Numerical assessment of residual formability in sheet metal products: towards design for sustainability

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Abstract. A new computational scheme is presented to addresses cold recyclability of sheet–metal products. Cold recycling or re-manufacturing is an emerging area studied mostly empirically; in its current form, it lacks theoretical foundation especially in the area of sheet metals. In this study, a re-formability index was introduced based on post-manufacture residual formability in sheet metal products. This index accounts for possible levels of deformation along different strain paths based on Polar Effective Plastic Strain (PEPS) technique. PEPS is strain-path independent, hence provides a foundation for residual formability analysis. A user-friendly code was developed to implement this assessment in conjunction with advanced finite-element (FE) analysis. The significance of this approach is the advancement towards recycling of sheet metal products without melting them.

1. Introduction

The environmental challenges have been considered as a serious problem across all industries, and reduction of energy and material consumption is a pressing matter for them. Conventional recycling saves significant amount of energy, however it involves melting process. High melting points of metals and additional processes required to get final products, turn it yet into an energy intensive process. Recycling metal waste without melting has potential for additional level of energy saving [1].

The possibility of cold recycling of sheet metals has been studied by some researchers. Takano et al. [2] showed that cold recycling of sheet metal can be accomplished using incremental forming, in which strain localization can be almost inhibited. Tekkaya et al. [3] analysed remanufacturing of a contoured sheet metal part using a hydro-forming technology. They showed that material inhomogeneity induced by a primary forming process could be ignored.

The main challenge in the cold recycling/remanufacturing process is varying and inhomogeneous material behaviour as a result of the primary forming process. Therefore, a very important requirement for re-manufacturing is the identification of residual formability across the material. As a matter of fact, the theoretical basis of remanufacturing has been barely addressed in the literature. The present research was an effort to bridge this gap by looking at the problem from a point of view of formability.

Forming limit diagrams (FLD) have been such an effective and widely accepted tool in sheet metal industries. A significant limitation of characterizing formability with the FLC was highlighted experimentally by Graf et al. [4] and it was concluded that no unified curve in a strain space could represent the forming limit of a material. Stoughton and Yoon [5] proposed an alternative approach as a remedy to the aforementioned difficulty. They modified the idea proposed by Zeng et al. [6] and employed effective plastic strain as a metric to evaluate formability. They suggested a PEPS diagram and demonstrated the insensitivity of their technique to a strain path using experimental data. Assuming a secondary life and additional forming stages for a formed product required multistage/multiple strain path formability assessment technique, therefore PEPS took the central stage in present research.

With an outlook for sustainable manufacturing, this study aimed at introducing an index that quantifies reformability of a pre-formed material on a scale of 0 to 1, that respectively denotes fully damaged and a healthy material. This index is strain-path-sensitive and provides an insight into the allowable formability for different strain paths.

2. Reformability index

Stoughton and Yoon [5] pointed out that, basically, two parameters carry nonlinear paths information on, first, β which is the ratio of the principal strain rates; and second, effective plastic strain $\bar{\varepsilon}_p$, which is defined by a time integral of a function of the principal strain rates. Assuming that principal strains, $\varepsilon_1(t)$ and $\varepsilon_2(t)$ are parameters accounting for the strain history, and r_m is the plastic anisotropy, the following relations are the components of the $PEPS$ diagram:

$$\bar{\varepsilon}_p(t) = \frac{1+r_m}{\sqrt{1+2r_m}} \int_0^t \sqrt{\dot{\varepsilon}_1{}^2(t') + \dot{\varepsilon}_1{}^2(t') + \frac{2r_m}{1+r_m}\dot{\varepsilon}_1(t')\varepsilon_1(t')dt'}, \quad (1)$$

$$\beta = \frac{\dot{\varepsilon}_2(t)}{\dot{\varepsilon}_1(t)}. \quad (2)$$

In order to plot diformation in a polar diagram of the $\theta = tan^{-1}(\beta)$, is measured with reference to vertical axis. Figure 1 illustrates PEPS diagram and how a multi-path operation can be examined against the limit curve.

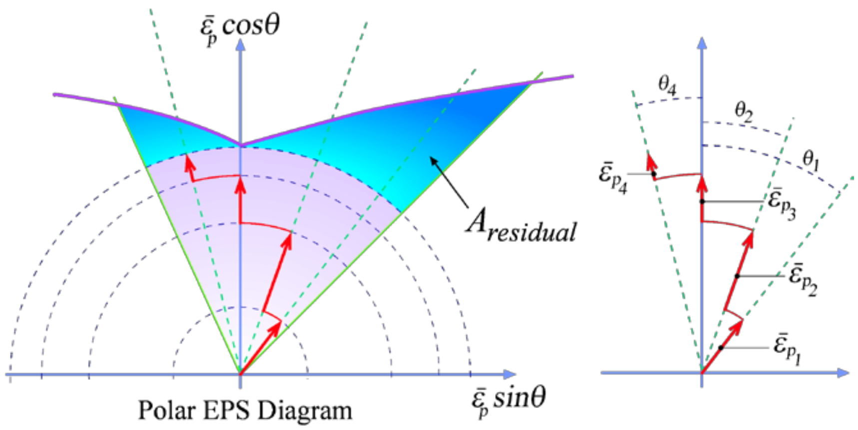

Figure 1. Graphical illustrations of Polar EPS diagram showing deformation with four different consecutive paths in which the progression of forming stages leads in loss of formability. In the proposed approach $A_{residual}$ is the basis for residual formability calculation.

2.1. *Strain-path-sensitive reformability index*

The technique proposed in this study is to calculate the area under the forming-limit curve and enclosed between the stress triaxiality $\eta = 2/3$ and $\eta = 1/3$, as a quantitative measure of original formability. Every stage of deformation exploit part of this area, and the residual formability can be described as the reduced area under the limit curve as shown in Figure 1. direction of the subsequent strain path is also an important parameter in describing the residual formability. Figure 2 illustrates that depending on strain-path the residual formability varies.

In the $PEPS$ approach, the circle passing through the end point of the effective strain vector is the locus of the starting point for next vector. This implies that after the deformation process a circular sector, consists of incremental deformations, would be taken off from the original formability. Therefore the reformability index can be formulated as:

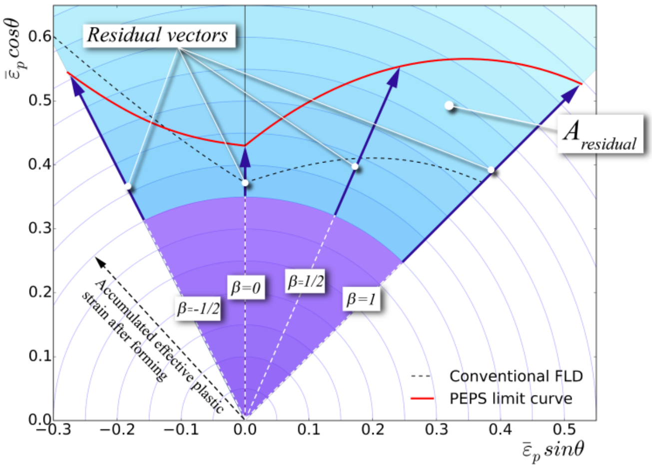

Figure 2. The ratio of residual area to original area; (A_r/A_0), does not address the residual formability in different strain path, therefore $\Phi = (A_r/A_0)^{B(\beta)}$ was introduced.

$$\Phi = \left(\frac{A_r}{A_0}\right)^{B(\beta)}, \tag{3}$$

$$A_0 = \frac{1+r_m}{\sqrt{1+2r_m}} \int_{\frac{-\pi}{8}}^{\frac{\pi}{4}} \sqrt{\varepsilon_{1FLD}{}^2 + \varepsilon_{2FLD}{}^2 + \frac{2r_m}{1+r_m}\varepsilon_{1FLD}\varepsilon_{2FLD}}\, d\theta\,, \tag{4}$$

$$A_r = A_0 - \frac{1+r_m}{\sqrt{1+2r_m}} \int_{\frac{-\pi}{8}}^{\frac{\pi}{4}} \int_0^t \sqrt{\dot{\varepsilon}_1{}^2(t') + \dot{\varepsilon}_1{}^2(t') + \frac{2r_m}{1+r_m}\dot{\varepsilon}_1(t')\dot{\varepsilon}_1(t')dt'}\, d\theta = A_0 - \bar{\varepsilon}_p\left(3\frac{\pi}{8}\right). \tag{5}$$

$$B(\beta) = C_3\beta^3 + C_2\beta^2 + C_1\beta^2 + C_0\,. \tag{6}$$

2.1.1. Calculating $B(\beta)$ constants. The exponent B is defined to modulate the reformability index to account for the strain-path effect. B is introduced as polynomial function of the strain path β.To calculate the associated constants, applying log function to both sides of the Eq. (3) gives:

$$B(\beta) = \frac{log\left(\frac{A_r}{A_0}\right)}{log\ (\Phi_\beta)}, \tag{7}$$

where A_r/A_0 is the residual to original area ratio, and Φ_β is the residual to original vector ratio for relevant strain path (see Figure 2). Four data values, are required to calculate C_0 to C_3. It is suggested to assume a total effective plastic strain equivalent to 70% of the limit curve in $\beta = 0$ direction, and workout $B(1)$, $B(1/2)$, $B(0)$ and $B(-1/2)$ from Eq.7. A set of four simultaneous equations are then obtained to calculating the polynomial constants.

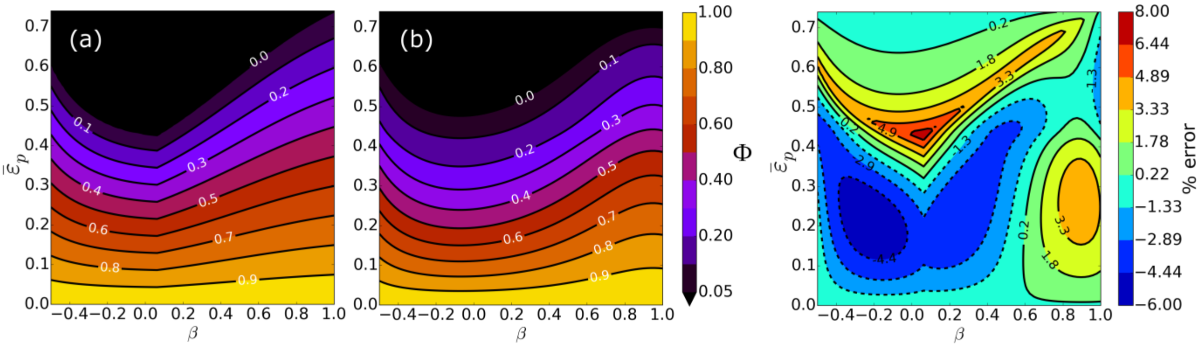

Figure 3. The strain-path sensitive reformability index (a) actual, (b) predicted and error.

A sample $B(\beta)$ for the *PEPS* curve is presented in Figure 3, in which "predicted" Φ index is shown together with the "actual" Φ obtained from vector ratios in every strain path angle. The error contour plot shows a good agreement between the model presented in Eq. (3) and the actual distribution. Higher order polynomial for $B(\beta)$ could improve the predicted Φ.

3. REFORMAP

Implementing this technique using the finite element provides an element by element assessment of reformability index across the part. A code called REFORMAP was developed for mapping out the reformability index downstream the FE simulation. Figure 4 shows a typical quarter model of rectangular deep drawn part. The presented FEA analysis is based on the analytical forming limit prediction. Once the result file is imported into REFORMAP, it helps visualizing the distribution of the reformability index and some additional analysis.

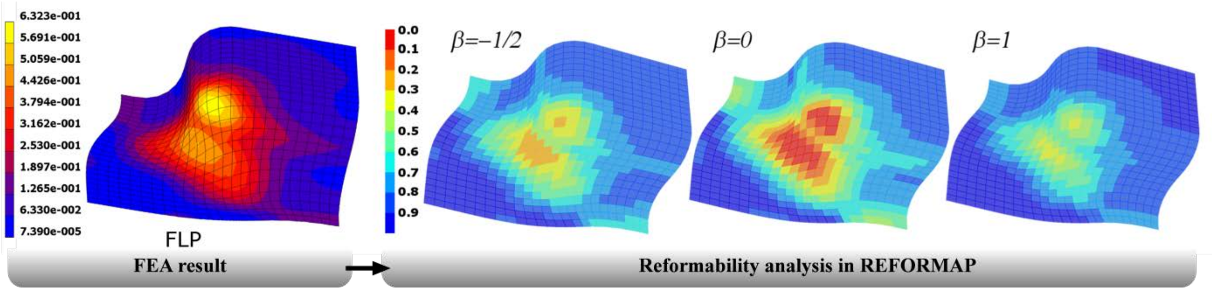

Figure 4. The results from FEA quarter deep drawing simulation was imported to REFORMAP for reformability analysis.

4. Conclusion

In this paper a strain-path-dependent index was proposed to quantify the reformability of deformed sheet on a scale from 0 to 1, denoting fully damaged and a healthy material respectively. This scheme was introduced based on the path independent Polar EPS. The proposed model was established and formulated in this paper, together with a way to obtain the relevant constants. The primary advantages of the PEPS are robustness against strain path change, and no dependence on the flow curve and any saturation or softening in the material model.

The presented model is suitable to be incorporated in numerical platforms. An in-house code called REFORMAP was developed to carry out reformability analysis downstream the FE simulation of forming process. The REFORMAP GUI provides three-dimensional visualization of the model as well as colour map of the re-formability index and other relevant outputs. This re-formability assessment implies the possibility of cold-recycling and contributes to design for recycling.

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