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Anisotropic effects in the compression beading of aluminum thin-walled tubes with rubber

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ABSTRACT

The purpose of this paper is to study numerically the "elastomer-assisted compression beading" (EACB process). It consists of conventional compressing beading after a local bulging carried out by an elastomer material. A Finite Element Method (FEM) is introduced to predict where and when the damage can occur in the tube and to study the effects of anisotropy on the occurrence of failure by cracking in regions where damage is accumulated. An anisotropic elasto-plastic constitutive model with mixed non-linear isotropic/kinematic hardening fully coupled with Lemaitre's ductile damage is implemented in ABAQUS/Explicit software via VUMAT subroutine. The influence of anisotropy on the damage evolution is investigated in this study and results are compared with isotropic model.

1. Introduction

Compression bead is a tube forming process that is widely used in industry. It can be used in attachment of tubes to sheets and damping vibrations in air-pressure lines, exhaust tubes or liquid systems. It consists of assembling one tube end towards the other with an initial gap between the two dies that hold the tube.

In local buckling of shell structures, substantial advances have been made since 1947. It has been proved that an ideal column will start to bend at a load equal to its tangent modulus load under axial compression [1]. The concept has been further investigated over the past decades. Tvergaard [2] studied the influence of the radius to the thickness ratio r_0/t_0 of the tube for deformation modes axisymmetric and non-axisymmetric. Alexander [3] recommended an analytical expression to calculate the buckling load of thin-cylindrical shells. More recently, several researches have been interested in tube end forming [4,5]. In their works, authors conducted experimental and theoretical studies on expansion and reduction of thin-walled tubes using a die. Centeno et al. [6] performed an experimental and numerical study of tube expansion with a tapered conical punch to determine the fracture strains and the critical values of ductile damage at the onset of failure by fracture in thin-walled tube forming. In the scope of this investigation, Gouveia et al. [7] performed a theoretical and experimental investigation on compression beading and nosing of AA6060 Aluminum alloy tubes. According to authors, number of tube beads depends on initial gap opening and wall thickness. The two key operative parameters were the ratio of the initial gap opening to the radius of the tube ($Lgap/r_0$) and the ratio of the radius to the thickness (r_0/t_0). When the ratio r_0/t_0 has high values, compression beads are formed both outward and inward. For little values of this ratio, compression beads become outward.

In what concerns industrial applications of the compression beading process for connecting tube to tube or tubes to sheet, it has been concluded that the most important parameter that influence significantly the compression beading is the initial gap opening Lgap [8,9]. Alves and Martins [10] were interested in studying tube branching by asymmetric compression beading. A minimum threshold of the slenderness ratio was defined to prevent the development of multiple instability waves. Also, they affirmed that the use of internal mandrel may avoid the geometric defects along the inner surface of the tube. Alves et al. [11] studied mechanical joining by plastic buckling of hollow polyvinylchloride profiles with various cross sections. Authors affirmed that the critical load at the onset of plastic buckling increases with the number of sides. The formation of wrinkles is limited to values of the slenderness ratio $Lgap/r_0$.

Other works performed thin-walled tubes forming with the assistance of elastomers as pressure transmitting medium. In the early 1970s, Al-Qureshi [12,13] investigated the rubber forming technique by studying parameters that can affect metal deformation mechanisms with elastomer materials. Furthermore, Al-Qureshi and Das [14] showed that it is possible to size and crop thin tubes by the use of elastomers. Later, with the aid of the elastomer forming technique, several works performed the forming of a junction on thin walled metal tubes [15,16]. Balendra and Qin [17] were interested in forming thick-

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walled tubes into hollow components using different pressurising media. Using urethane rod as flexible tool to bulge aluminum tubes, Thiruvarudchelvan [18] developed a theoretical prediction to determinate the required pressure transmitted by the rubber in bulging the tube. The elastomers were used later in compressing beading to investigate deformation mechanics of the EACB process by means of analytical modeling, numerical simulation and experimentation [19,20].

Several studies reported in literature are interested in analyzing the tube bulge forming process. Fuchizawa [21,22] analyzed bulge forming of thin-walled cylinders under internal pressure. Author showed the influence of strain hardening exponent on limits of bulge height. Asnafi [23,24] performed theoretical analysis that shows what the limits are during free forming of tube, and how different material and process parameters influence the loading path. Later, other works tried to optimize tube hydroforming process parameters in the free bulged region of the tube like thickness distribution, forming pressure, axial loading and tube profile [25–27]. Nevertheless, these works don't consider anisotropic effects of tubular material. In other studies, to consider an initial anisotropy in tubular materials, the orthotropic Hill's criterion was adopted to analyze the plastic deformation behavior of thin-walled tube under bulge forming process [28]. Also, considering plastic anisotropy, Kim et al. [29] predicted numerically bursting failure in tube hydroforming by the FEM. Authors concluded that bursting pressure increases with the relatively increasing of the R-value.

In view of what has been said above, one can notice that studying ductile damage in overall EACB process is rarely found in the research literature. Even the effect of some parameters like anisotropy on the evolution of damage is neglected.

Under these circumstances, the effects of anisotropy on the occurrence of ductile damage will be studied in this investigation in order to better understanding the deformation mechanics of the EACB process. Based on previous works of Wali et al. [30–32], Lemaitre's ductile damage coupled to the anisotropic Hill criterion is formulated and validated in [33,34]. This implementation is used in this work to predict evolution of damage throughout the formed part of the tube. A Mooney–Rivlin model is used to define the hyper-elastic behavior of rubber. The contribution of this paper consists in the fully coupling between the anisotropic elasto-plastic model based on Hill'1948 anisotropic criterion associated with mixed non-linear isotropic/kinematic hardening (NLKH) and the ductile damage model applied to EACB process. A comparison between the isotropic J_2 model and the anisotropic Hill-NLKH model in term of evolution of damage is conducted. The effect of hardness of the rubber is also analyzed.

2. Constitutive model

2.1. Fully coupled constitutive equations

The constitutive equations used in this paper are relative to plastic anisotropic formulation accounting for non-linear isotropic and kinematic hardening coupled with isotropic ductile damage of Lemaitre and Chaboche [35]. Table 1 presents the overall fully coupled constitutive equation of anisotropic Hill criterion to the Lemaitre continuum damage model.

In Table 1, $\boldsymbol{\varepsilon}^e$ and $\boldsymbol{\varepsilon}^p$ are the elastic and plastic strain tensor respectively, r and R are the isotropic hardening variables, $\boldsymbol{\alpha}_k$ and $\mathbf{X}_k$ are the kinematic hardening variables, d and Y are isotropic ductile damage variables, a_k, b_k, δ, β, s, S and Y_0 are material parameters and finally $\mathbf{P}$ is a fourth order tensor. In three-dimensional cases, it is given by

Table 1
Complete set of the constitutive equations.

a/Stress tensor	d/Isotropic hardening
$\boldsymbol{\sigma} = (1-d)\mathbf{D}:\boldsymbol{\varepsilon}^e$ (1)	$R = R(r)$ (6)
b/Damage force	e/Kinematic hardening:
$Y = \frac{1}{2}\boldsymbol{\varepsilon}^e:\mathbf{D}:\boldsymbol{\varepsilon}^e$ (2)	$\mathbf{X} = \sum_{k=1}^{M}\mathbf{X}_k,\quad \dot{\mathbf{X}}_k = a_k\dot{\boldsymbol{\varepsilon}}^p - \dot{\gamma} b_k \mathbf{X}_k$ (7)
c/Yield criterion	f/Plastic strain tensor:
$f = \frac{1}{(1-d)^{\delta}}\varphi(\boldsymbol{\xi}) - (\sigma_Y + R)$ (3)	$\dot{\boldsymbol{\varepsilon}}^p = \frac{\dot{\gamma}}{(1-d)^{\delta}}\mathbf{n},\quad \mathbf{n} = \frac{1}{\varphi}\mathbf{P}\boldsymbol{\xi}$ (8)
$\boldsymbol{\xi} = \boldsymbol{\sigma} - \mathbf{X},\ \varphi = \sqrt{\boldsymbol{\xi}^t\,\mathbf{P}\,\boldsymbol{\xi}}$ (4)	g/Isotropic damage rate:
Loading/unloading condition:	$\dot{d} = \dot{\gamma}\,\overline{Y},\quad \overline{Y} = \frac{1}{(1-d)^{\beta}}\left\langle\frac{Y-Y_0}{S}\right\rangle^{s},$ (9)
$\dot{\gamma} \geq 0,\ f \leq 0,\quad \dot{\gamma} f = 0$ (5)	

$$\mathbf{P} = \begin{bmatrix} H+G & -H & -G & 0 & 0 & 0 \\ & H+F & -F & 0 & 0 & 0 \\ & & F+G & 0 & 0 & 0 \\ & & & 2N & 0 & 0 \\ & Sym & & & 2M & 0 \\ & & & & & 2L \end{bmatrix} \tag{10}$$

2.2. Numerical integration scheme

An algorithm based on fully implicit backward Euler integration is developed. This numerical integration procedure of elastoplastic problems is unconditional stability. The used integration algorithm is a strain-driven algorithm where the stress history is obtained from the strain history. Based on the constitutive equations given in Table 1, the trial stress can be defined as

$$\boldsymbol{\sigma}^{trial} = \boldsymbol{\sigma}_n + (1-d_n)\mathbf{D}\Delta\boldsymbol{\varepsilon} \tag{11}$$

then the stress tensed is expressed as

$$\boldsymbol{\sigma}_{n+1} = \frac{1-d_{n+1}}{1-d_n}\boldsymbol{\sigma}^{trial} - \frac{\Delta\gamma}{(1-d_{n+1})^{\delta-1}}\mathbf{D}.\,\mathbf{n}_{n+1} \tag{12}$$

and finally

$$\boldsymbol{\xi}_{n+1} = \mathbf{I}_c^{-1}.\,\overline{\boldsymbol{\xi}},\quad \mathbf{I}_c = \mathbf{I} + \frac{u}{(1-d_{n+1})^{\delta}}[(1-d_{n+1})\mathbf{D} + a_{\omega}\mathbf{I}]\mathbf{P},\quad u = \frac{\Delta\gamma}{\varphi_{n+1}} \tag{13}$$

$$\text{with}\quad \overline{\boldsymbol{\xi}} = \frac{1-d_{n+1}}{1-d_n}\boldsymbol{\sigma}^{trial} - \sum_{k=1}^{M}\frac{1}{\omega_k}\mathbf{X}_{k,n},\quad a_{\omega} = \sum_{k=1}^{M}\frac{a_k}{\omega_k} \tag{14}$$

It then follows that only two scalar equations is to be solved which are the consistency condition and the damage equation, see [32,33].

$$\begin{cases} f_1(\Delta\gamma, d) = \frac{\varphi}{(1-d)^{\delta}} - \sigma_p = 0 \\ f_2(\Delta\gamma, d) = d - d_n - \Delta\gamma\overline{Y} = 0 \end{cases},\quad \begin{cases} \sigma_p = \sigma_Y + R \\ \varphi = [\overline{\boldsymbol{\xi}}^T.\ \mathbf{I}_c^{-T}.\ \mathbf{P}\ .\ \mathbf{I}_c^{-1}.\ \overline{\boldsymbol{\xi}}]^{1/2} \end{cases} \tag{15}$$

The unknowns of this system of equations are the plastic multiplier $\Delta\gamma$ and the damage variable d.

The system of, Eq. (15), is solved with the Newton-Raphson method. The governing equations of one step of Newton-Raphson iteration scheme are summarized in Table 2.

The local iteration given in Table 2 can be used either for plane stress or 3D problems. The two scalar, Eq. (15), represent a low number