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Fracture limit prediction for roller hemming of aluminum alloy sheet

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ABSTRACT

Roller hemming limit is predicted based on ductile fracture criterion in this approach. Plastic deformation in sheets made of aluminum alloy 6061-T6 is studied experimentally. Combined isotropic and kinematic hardening rule is considered in roller hemming numerical analysis. Forming limit stress curve at fracture (FLSCF) is derived from Cockcroft–Latham ductile damage criterion to determine fracture during roller hemming simulation. Serrated strain paths are detected along hemline. The zones where fracture takes place obtained by experiments and FE simulations are compared. It is demonstrated that FLSCF, which is on the basis of ductile damage criteria and basically irrelevant to linearity of strain path could be used to predict fracture of roller hemming correctly.

1. Introduction

Hemming is an important assembly process for the body-in-white opening parts, such as doors, deck lids and hoods [1]. Hemming needs to fold the edge of an outer piece over an inner one. Classical tabletop hemming is costly for its investment on large-scale special hemming die. Now roller hemming has began to take place the traditional tabletop hemming because of its flexibility.

In this process, a roller is guided by a robot along the hemmed line progressively bending the flanged height along the part [2]. The basic idea of roller hemming is to obtain the desired shape of the part through the movement of roller along a user-specified path. Thus a robot is used to plastically deform the blank, imposing to the tool an assigned trajectory controlled by computer. In this way, no conventional dies is required and the final shape of the part only depends on the trajectory assigned to the tool. The simple reasoning above shows that roller hemming permits a relevant reduction of the costs linked to die manufacture and setup. Roller hemming could use only one tool from prototype to serial fabrication, which has the advantage of low cost, less delivery time in industrialization, high flexibility, etc. In this case the advantages offered by roller hemming in reducing time to market are discernible.

Previous studies are mostly focused on tabletop hemming. Livatyali et al. [3–8] studied the effects of flanging and hemming parameters on tabletop hemming quality. Zhang et al. [9,10] investigated the mechanism of hemming warp and recoil. Muderrisoglu et al. [11] analyzed influences of flanging parameters on roll-in/out of 1050 aluminum alloy tabletop hemming. Lin et al. [12] presented maximum surface strain as a hemming fracture criterion. Thuillier [2,13] focused on the finite element simulation of tabletop hemming and roller hemming process of an Al–Mg alloy on roll-in/out.

However, a highly localized severe plastic deformation along the exterior surface of the outer panel appears during roller hemming. The deformation may be associated with damage occurrence during hemming operations, especially for those weak ductility material compared with steel. Aluminum alloy, which is a substitute of steel for light-weight design, has been used for the production of vehicle outer panels. It has a weakness of low formability, which results in the severity of roller hemming fracture. Thus, prediction of fracture during roller hemming is important. The limit strain before failure is called the fracture limit. Nevertheless, forming processes like conventional stamping is limited by instabilities, which refers to a situation that the deformation gets concentrated into a small region (the neck) while material does not deform any further. Consequently, the limit is called the necking limit [14]. The best known example of a necking limit is the conventional forming limit curve. As for roller hemming, formability is limited by fracture. Currently, the mechanism of hemline surface fracture is not well understood, and designers need a criterion for roller hemming formability evaluations. Le Maout [15] made a prediction of tabletop hemming fracture by a critical value of the void volume fraction.

The so called forming limit curve at neck (FLCN) is considered effective for fracture prediction by forming limit curve at fracture (FLCF) during roller hemming. Nevertheless, forming limit strain curve is always associated with linear strain paths. Forming limit stress curve which is previously thought to have no connection with strain path complexity could be proposed as a criterion to determine fracture limit [16].

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This paper presents a study on roller hemming forming limit at fracture for aluminum alloys using ductile damage theory. The aluminum alloy 6061-T6 is first presented. The non-linear kinematic hardening rule is then used, as well as the mechanical tests used to characterize the parameters. Later the description of roller hemming process simulation which takes ductile damage into account is given and the adoption of forming limit stress curve at fracture (FLSCF) based on Cockcroft and Latham ductile criterion is illustrated to predict fracture.

2. Methods

A simple phenomenological criterion proposed by Cockcroft and Latham [17] assumes ductile fracture happens when

$$W = \int_0^{\bar{\varepsilon}} \max(\sigma_1, 0) d\bar{\varepsilon} \geqslant W_C, \quad (1)$$

where σ_1 is the maximum principal stress and W_C is the critical value of the integral W.

The Cockcroft–Latham fracture criterion has only one parameter, W_C, which could be determined from uniaxial tensile experiments. Considering only the exterior surface is concerned for fracture, a plane-stress condition is assumed throughout roller hemming. And FLSCF is thought to be irrelevant to strain path. Hence, further assumption of constant strain ratio could be adopted. Meanwhile Deformation Theory of Constitutive Equation is effective for constant strain ratio. Consequently, FLSCF could be calculated from the stated assumptions including stress strain curve, plane-stress condition, linear strain path, Deformation Theory of Constitutive Equation, Cockcroft–Latham fracture criterion, etc.

3. Results and discussion

3.1. Material parameters identification

The aluminum alloy sheet 6061-T6 (chemical composition in wt.%, see Table 1) was considered in the present investigation.

Uniaxial tensile tests were carried out at room temperature by using a conventional servo-hydraulic testing machine. Tensile specimens in accordance with the China GB/T228-2002 standard (Fig. 1), 1.0 mm thick and with a 12.5 mm wide gauge section, were cut along the rolling direction (0°), 45° to the rolling direction and in the transverse in-plane direction (90°).The gauge length of the specimen was 40 mm. The specimens were stretched to fracture under displacement control at a constant cross-head speed of 1.8 mm/min. Load–deformation curves were obtained. The R values (plastic strain ratio) are then determined from

$$R_\alpha = \frac{\varepsilon_w^p}{\varepsilon_t^p} = \frac{\varepsilon_w^p}{\varepsilon_l^p + \varepsilon_w^p}, \quad (2)$$

where α denotes the orientation to the rolling direction, while ε_l^p and ε_w^p refer to the longitudinal and transverse logarithmic plastic strains of gauge section, respectively. The logarithmic plastic thickness strain, ε_t^p, is calculated by assuming plastic incompressibility.

Typical mechanical properties of 6061-T6 obtained by uniaxial tension tests are presented in Table 2.

The average stress at 0.2% permanent plastic strain was found to be approximately 147 MPa and the ultimate tensile strength was about 281 MPa. Engineering stress–strain curves describing the work hardening behavior in each orientation are shown in Fig. 2. From the obtained R values for each orientation, the strength and plastic flow anisotropy is seen to be minor and it was therefore decided to neglect plastic anisotropy in the elastoplastic constitutive model established for 6061-T6.

A phenomenological constitutive model for 6061-T6 roller hemming is presented in this section. Since the material exhibits only weak anisotropic behavior, it was chosen to use an isotropic yield model. Moreover, roller hemming concerns to a complex forth and back forming process. Therefore, an elastoplastic constitutive model with an isotropic yield criterion, a non-linear kinematic hardening rule and the associated flow rule is considered.

The yield criterion $f = \bar{\sigma} - (\sigma_0 + R) \leqslant 0$ defines the elastic domain, where σ_0 is the initial yield stress. The effective stress $\bar{\sigma}$ is defined in terms of Von Mises yield criterion by

$$\bar{\sigma} = \sqrt{\frac{3}{2}(\sigma_{ij} - \alpha_{ij})^2}, \quad (3)$$

where σ_{ij} and α_{ij} are the flow stresses and back stresses.

Isotropic hardening part R is defined by Voce rule

Table 1
Chemical composition of the aluminum alloy 6061-T6.

Mg	Si	Cu	Cr	Fe	Mn	Zn	Ti
0.8–1.2	0.4–0.8	0.15–0.40	0.04–0.35	⩽0.7	⩽0.15	⩽0.25	⩽0.15

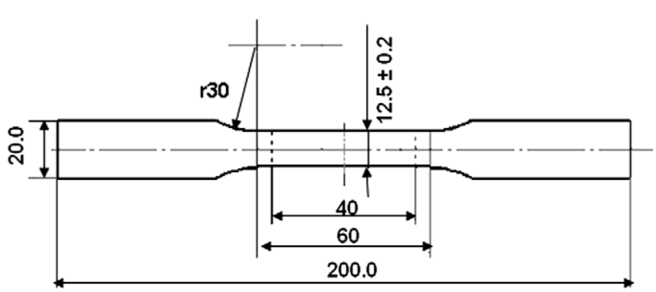

Fig. 1. Uniaxial tension specimen.

Table 2
6061-T6 material properties.

	Yield stress (MPa)	Tensile stress (MPa)	Plastic strain ratio, R
0°	148.4	283.9	0.675
45°	147.6	278.9	0.708
90°	146.2	280.7	0.663

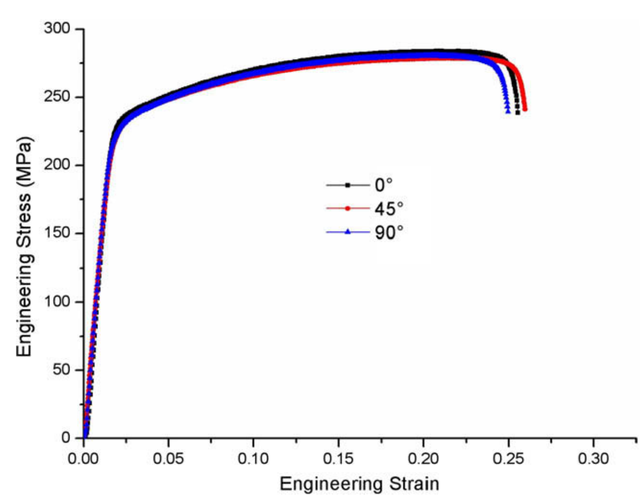

Fig. 2. Engineering stress–strain curve for different orientations.