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A buckling model for flange wrinkling in hot deep drawing aluminium alloys with macro-textured tool surfaces

Kailun Zheng[a], Junyi Lee[a], Jianguo Lin[a,*], Trevor A. Dean[b]

[a] Department of Mechanical Engineering, Imperial College London, Exhibition Road, London SW7 2AZ, UK
[b] School of Mechanical Engineering, University of Birmingham, Edgbaston, Birmingham B15 2TT, UK

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ABSTRACT

The work described in this paper is the development of a buckling model based on the classical energy method of flange area material using a one-dimensional beam geometry assumption to predict flange wrinkling in hot deep drawing aluminium alloys with macro-textured blankholder surfaces. A series of deep drawing experiments utilising different macro-textured tool surfaces were performed to investigate the effects of process parameters and texture features on flange wrinkling. The results have shown that wrinkling occurs when the hollow dimension of radially grooved textures reached a certain magnitude dependent on process conditions. A dislocation-driven based continuum damage mechanism (CDM) material model for aluminium alloys at elevated temperatures was used to model the viscoplastic behaviour during deformation. The newly developed buckling model was validated by comparison with experimental results. The predicted results showed that the resistance to wrinkling increases with increasing forming temperature and decreasing forming speed, depending on the particular viscoplastic characteristics of the work-piece. The effects of texture ratio and draw ratio on wrinkling were found to be more significant than the effects of the temperature and strain rate. The buckling model developed in this paper can be used to model the flange wrinkling phenomena, as well as the non-isothermal feature in the hot stamping condition using the macro-textured tool surfaces.

1. Introduction

Increasing economic and environmental concerns have driven the need for lighter but safer structures in the transportation industry, making lightweight materials, such as aluminium and magnesium alloys, popular candidates for automotive and aerospace applications [1–4]. A large proportion of body structures is made of formed sheet metal. To overcome the poor ductility of aluminium alloys at room temperature and manufacture complex-shaped components, a novel hot stamping process, named solution heat treatment, hot forming and cold die quenching (HFQ®), was proposed and patented by Lin et al. [5]. HFQ® is now a leading edge technology in this area [6,7]. Apart from exploiting the viscoplastic behaviour of aluminium alloys at elevated temperatures, hot stamping at solution heat treatment temperatures can also increase ductility due to the dissolution of the initial coarse precipitates for heat-treatable aluminium alloys [8]. The obtained optimum microstructure can then be "frozen" using cold die quenching after hot stamping and the formed component can be artificially aged to maximum strength to meet strength requirements. The non-isothermal feature of hot stamping processes due to the heat transfer between the hot work-piece and the cold dies results in non-uniform deformations, which affect hot formability significantly. This issue can be alleviated with the use of macro-textured tool surfaces, such as the one introduced by Zheng et al. [9]. The use of textured tools significantly reduces the contact area and heat transfer compared to traditional flat tool designs. This results in a more uniform temperature distribution within the work-piece, which improves the deformation uniformity and thereby increases the drawability of hot stamping aluminium alloys.

However, tool designs with textured hollows may result in flange wrinkling for complex-shaped components that are formed under complicated stress states. The occurrence of flange wrinkling was found to be related to the dimensions of the textured hollows. To maximize the function of macro-textured tool surfaces and determine the critical texture dimensions, finite element (FE) method can be used to model material deformation under different texture designs, which requires huge amount of simulations to obtain the critical dimension, and the accuracy also is determined by the wrinkling criterion of a particular FE software. Hence, an analytical buckling model for predicting the flange wrinkling for specific macro-textured tools would

* Corresponding author.
E-mail address: Jianguo.lin@imperial.ac.uk (J. Lin).

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be a useful guide to facilitate wrinkling prevention by industrial tool designers efficiently and provide fundamental understanding of wrinkling occurrence.

Flange wrinkling phenomena have been investigated extensively through models by the mechanism of buckling in sheet metal forming processes. Senior [10] has established a flange wrinkling model based on the energy method for the deep drawing process without blankholder. In this model, the flange material was assumed as a one-dimensional beam and is accurate only when the flange width is small compared with work-piece radius. Yu and Johnson [11] applied the two-dimensional elastic-based rigid-plastic stability theory to analyse the flange wrinkling behaviour in the deep drawing process. The established buckling model was capable of predicting the occurrence and wave number of flange wrinkling. These buckling models applied a reduced modulus [12] to reflect the material behaviour when the stress is beyond the elastic limit, which eases the analysis at a reasonable loss of accuracy. Apart from that, Hutchinson et al. [13,14] have also proposed a bifurcation function based on Hill's general theory of uniqueness and bifurcation of elastic-plastic solids [15] to predict the plastic wrinkling of shells. The buckling model based on the bifurcation theory can be extended further for anisotropic materials using Hill's non-quadratic yield criterion [16] and the six-component yield function of anisotropic materials [17,18]. Besides the popular buckling models described above, a C-B wrinkling criterion based on the energy conservation principle has been proposed [19,20]. The effects of the blankholding force were considered in the C-B criterion, and the proposed buckling models were validated by experimental results using a rectangular shaped component. The abundant buckling models in the literature described above are focused on cold forming conditions and are inapplicable to the hot stamping processes of aluminium alloys that are gaining widespread use in recent times. The work in this paper aims to provide flange wrinkling models that are appropriate for the application of these new technologies.

The prediction of flange wrinkling for hot stamping is not trivial. Unlike materials at room temperature, viscoplastic behaviours dominate deformation at elevated temperatures, for alloys which are temperature and strain rate dependent [21]. Hence, the forming speed and thermal reaction during forming need to be considered and modelled in hot stamping processes [22]. Furthermore, the advanced macro-textured tool design used in hot stamping processes requires more factors, such as the geometry, displacement expressions, and boundary conditions, to be considered.

In this paper, a buckling model of the flange wrinkling phenomenon in hot stamping, based on the one-dimensional beam geometry assumption, using an energy method is developed the first time. This enables the occurrence of flange wrinkling to be predicted for different tool surface texture designs and the non-isothermal feature of hot stamping to be modelled. A series of corresponding deep drawing experiments have been performed to validate the developed model. In addition, the effects of forming temperature, forming speed, texture ratio, and draw ratio on the occurrence of flange wrinkling were investigated experimentally and analytically.

2. Experimental set-up

2.1. Work-piece material and experimental tool set

The selected work-piece material was commercial aluminium alloy AA6082-T6 condition provided by Smith Metal UK, which was machined to circular work-pieces with diameters: 170, 180, and 190 mm. The chemical composition of work-piece material is given in Table 1.

Table 1
Chemical composition of AA6082.

Element	Mn	Fe	Mg	Si	Cu	Zn	Ti	Cr	Al
%	0.4–1.0	0.5	0.6–1.2	0.7–1.3	0.1	0.2	0.1	0–0.25	Balance

The components of the cylindrical hot deep drawing process using a textured tool surface are shown in Fig. 1(a). Fig. 1(b) shows the dimensions of the tools that contacted the work-piece. A flat-nosed punch, 100 mm diameter and 10 mm corner radius, was used for the deep drawing experiments, which involved different draw ratios ($DR = D_{work-piece}/D_{punch}$). The draw ratios used in the experiments were 1.7, 1.8, and 1.9. The macro-scale texture rectangular grooves were machined on only the lower blankholder. The grooves were radial so as to avoid the constraint effect of macro-textures not parallel to the material flow direction [23]. These textures can be divided into two features: the groove and the surface, as shown in Fig. 1(c), which is a plan view of a quarter of the macro-textured blankholder. The depth of each groove was 1 mm. The size of each feature is characterised by the radial angle of the groove. Surface and groove arc angles were defined as θ_S and θ_G respectively. To reflect the magnitude of texture geometry variation, a texture ratio α is defined as the ratio between the groove and surface arc angles, Eq. (1). The radial angle of the surface θ_S was 2.5° for all the textured tools. The ratio $\alpha = 0$ represents a non-textured flat surface, which has uninterrupted contact with the work-piece, and the ratio $\alpha = \infty$ represents a knife-edge contact with the work-piece. The blankholder was supported on a gas cushion system via a support frame, which also supplied the blank holding force. Four geometries of blankholder surface were used, a plane surface and three macro-textured surfaces. The corresponding texture ratios used in the experiments were: $\alpha = 0,1,3,5$. The horizontal die surface, which was part of the blankholder, was flat. The die was attached to the ram of a 250 kN ESH hydraulic press with a maximum forming speed of 500 mm/s and a total stroke of 200 mm.

$$\alpha=\theta_G/\theta_S \tag{1}$$

2.2. Experimental procedure

Fig. 2 shows the temperature profile of a work-piece during experiments. The as-received work-piece material was first solution heat treated to dissolve the initial coarse precipitates into the aluminium matrix and rapidly cooled to room temperature to obtain a supersaturated solid solution state. In order to investigate the effects of forming temperature and forming speed on flange wrinkling, the quenched work-piece was heated again to the target temperatures and deep drawn using different macro-textured blankholders at different forming speeds. Two typical forming temperatures were selected, 350 °C and 450 °C, and the forming speeds were 75 mm/s and 300 mm/s. Table 2 shows the process parameters.

2.3. Typical hot stamped parts

Fig. 3 shows typical hot stamped parts using macro-textured blankholders with different texture ratios at a forming temperature of 350 °C and a forming speed of 300 mm/s. The draw ratio was 1.8, and the blankholding force was 10 kN. As shown in the figure, the degree of flange deformation was determined by the texture ratio on the blankholder. Using flat blankholder and textured blankholder with a ratio, 1, work-piece material were successfully drawn to circular cylinders, as shown in Fig. 3(a) and (b) respectively. While severe flange wrinkling occurred for texture ratios, 3 and 5, as seen in the Fig. 3(c) and (d). The extent of wrinkling was evaluated visually.

Using the small texture ratio of 1, the work-piece can be successfully drawn in with a slightly wrinkled outer edge that can be ironed in, which is believed to be caused by two reasons as illustrated in Fig. 4. Fig. 4(a) shows the schematic diagram of material deformation at flange region using the textured tool design. The dash line represents