International Journal of Mechanical Sciences 140 (2018) 51–59

Contents lists available at ScienceDirect

International Journal of Mechanical Sciences

journal homepage: www.elsevier.com/locate/ijmecsci

Investigation of anisotropy effects on sheet-bulk forming of duplex gear parts

Xiaolong Sun, Xincun Zhuang, Zhen Zhao*

Institute of Forming Technology & Equipment, School of Materials Science and Engineering, Shanghai Jiao Tong University, Shanghai 200030, China

ARTICLE INFO

Keywords:
Sheet-bulk metal forming
Anisotropy effects
Lankford coefficients
Cube compression test

ABSTRACT

Sheet-bulk metal forming, as a new process applied bulk forming on sheet metal to obtain high-quality parts with low weight, attracts the interest of automobile industry for lightweight beneficiation. In this study, the effects of anisotropy on the bulk forming of sheets under large strain were investigated. A duplex gear part of 1060 and 6061 aluminum with several types of teeth was taken as a target part. The billets were located in three different directions during forming. The forming results obtained under stroke settings of 2.0 mm (Al1060) and 1.9 mm (Al6061) were used to measure anisotropy effects. Hill's 48 model was chosen as the anisotropic model. The Lankford coefficients in the model were obtained from uniaxial tension test and cube compression test. The comparison of the data from experiments and the numerical model demonstrated that Hill's 48 model (with Lankford coefficients obtained from cube compression test) most accurately predicted the anisotropy during the sheet shearing and upsetting process.

1. Introduction

The anisotropy of sheet metals, which may lead to geometrical asymmetries such as earing in tension states [1], is widely known in sheet forming. Different models, such as Hill's model [2] and Barlat's model [3], can be used to predict anisotropic behavior during sheet forming. For billets that are cut from bars after the extrusion, textures exist along the bar's direction of extruding. Han [4] studied the effects of anisotropy on extruded annealed aluminum by using ring compression test in samples obtained in different directions along bars. For billets cut from cast bars, the textures are not obvious. In some other billets, the textures of billets are identical in the axisymmetric plane; the forming can be simplified to a symmetrical model. Therefore, anisotropy is not a concern in most bulk forming operations.

Sheet-bulk metal forming (SBMF) has attracted considerable interest from the automobile industry, in which lightweight parts can be environment-friendly [5]. Some typical billets like synchronizer are obtained from sheet metal; the textures of the billets are not identical in any axisymmetric plane; thus, material behaviors in various directions are not the same. Some researchers have investigated anisotropy during SBMF by using experiments and numerical simulation. Merklein [6] considered anisotropy by employing layer compression test to investigate material behaviors under uniaxial compression loading of sheet metal. Sato [7] considered anisotropy when studying the forming limit in 4-mm-thick sheet forging. Zhuang [8] used inverse analysis in compression test of a medium sheet and measured the influences of anisotropy on hole flanges in a rim-hole process. Landkammer [9] used local press forming to investigate the orthotropic behaviors in SBMF. Kitamura [10] investigated anisotropy distributions in the thickness direction of 15 mm thick sheet metal and the effects on the cylinder and cube compression test in large strain deformation.

In this study, a sheet-bulk metal forming process was employed to investigate the effects of anisotropy on complex teeth forming. Such anisotropy might lead to differences in material flow during the deformation. As depicted in Fig. 1, the teeth in area A are fulfilled, at which time the teeth in area B are still underfilled; this type of material flow might cause die cracks in area A during continuous forming. In the hope of preventing such events, the influences of anisotropy on material flow were investigated by using both experiments and simulations in the present study. The anisotropic model chosen was Hill's 48 model, and the Lankford coefficients were obtained from tensile test in tension states and cube compression test in compression states.

The remainder of this paper is structured as follows. In Section 2, the procedural details of the experiments are introduced. In Section 3, the numerical modeling using isotropic and anisotropic models are introduced. In Section 4, the forming results in the different directions of the experiments are analyzed. The simulation results are presented to compare with the results of the experiments in this section. Based on the results from the experiment and simulation, the anisotropic influences on the material flow during the sheet shearing and upsetting are discussed. Finally, the findings are summarized in Section 5.

---

* Corresponding author.
E-mail address: zzhao@sjtu.edu.cn (Z. Zhao).

https://doi.org/10.1016/j.ijmecsci.2018.02.050
Received 15 November 2017; Received in revised form 11 February 2018; Accepted 27 February 2018

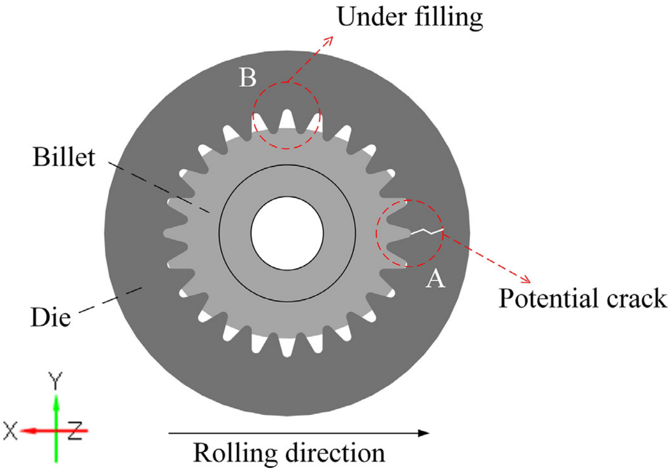

Fig. 1. Schematic of anisotropic effects during the deformation.

2. Experimentation

A duplex gear with various types of teeth, as shown in Fig. 2, was chosen as the target part. There is a hole with diameter of 8 mm in the center of the part. The height of all inner teeth was t_1; the height of all outer flanges was t_2. The gears were divided into eight different areas, each of which had same type teeth, and the detail of some teeth are listed.

The process used could be viewed as a compound shearing and upsetting process. The key elements of the tool set are shown in Fig. 3. The ring billet was located on the mandrel and stationary die; as the punch moved downward, the inner teeth were under shearing and outside area was under upsetting.

The forming sequence can be seen in Fig. 4. The first stage was a shearing and upsetting stage. When the teeth in the outside area began to contact the gear of the die, the second stage began. The second stage was a divided flow forging stage. In particular, the shearing and upsetting forming state of a stroke setting of 2.0 mm of Al1060 and a stroke setting of 1.9 mm of Al6061 were studied.

The two materials used in the experiment were Al1060 under H24 state and fully annealed Al6061. The thicknesses of the sheet metal (t_0) were 4.5 mm for 1060-H24 and 4.1 mm for 6061-O. The billets were ring-shaped. The inner diameters of both samples were 8 mm, and the outer diameters were 27.6 mm for 1060-H24 and 26.8 mm for 6061-O. The rolling direction was marked on the billets. The billets were laid on the tool set with various orientations, as shown in Fig. 5. The red outline is the gear shape of the punch; the billets with rolling marks were oriented at 0°, 45°, and 90° with the big flat tooth in area A of the punch. The billets were lubricated with oil of RENOFORM MZAN 51 H provided by FUCHS.

The samples obtained from the experiments (Fig. 6(b)) were scanned using ATOS core scanning equipment (Fig. 6(a)) with a measurement error of 0.01 mm, and three-dimensional STL files were obtained. By comparison with the target part, the shear droop size of inner teeth and the gaps of all outer teeth were measured.

3. Numerical modeling

The simulation was performed using Forge NxT1.1 software. The forming speed was set as 1 mm/s and friction was set as a shear friction model with a factor of 0.12, a value that had been obtained through a ring compression test. The spring load on the floating die was 30 kN/0.4 mm.

Material flow curves were obtained through cylinder upsetting and fitting with Hollomon's law. The anisotropic model was chosen as Hill's 48 model as expressed in function (1).

$$F\cdot(\sigma_{22}-\sigma_{33})^2+G\cdot(\sigma_{33}-\sigma_{11})^2+H\cdot(\sigma_{11}-\sigma_{22})^2+2L\cdot{\sigma_{23}}^2 \\ +2M\cdot{\sigma_{13}}^2+2N\cdot{\sigma_{12}}^2={\sigma_0}^2 \tag{1}$$

Where *F, G, H, L, M* and *N* are Hill's anisotropic parameters, which can be expressed by Lankford coefficients (*r*-value). The value of parameters *L* and *M* are regarded equal to *N* in this research.

$$F=\frac{r_0}{r_{90}(r_0+1)},\ G=\frac{1}{r_0+1},\ H=\frac{r_0}{r_0+1},\ N=\frac{(r_0+r_{90})(1+2r_{45})}{2r_{90}(r_0+1)} \tag{2}$$

Lankford coefficients (*r*-value) are obtained from the equation as (3), where ε_w and ε_t is the true strain in width and thickness respectively.

$$r=\frac{\varepsilon_w}{\varepsilon_t} \tag{3}$$

Uniaxial tensile tests in three directions (0°, 45°, and 90°) were performed to obtain the Lankford coefficients in tension states [11], and compression tests using cube samples were applied to obtain the Lankford coefficients in compression states [12]. The details of the mechanical property test, particularly the specimens before and after the test, are summarized in a graphical form as shown in Fig. 7.

The flow curves of the material were obtained using cylinder compression tests under room temperature and fitted with Hollomon's equation. The Lankford coefficients of tension states (*RL*), were obtained from uniaxial tension tests under strains of 0.08 for Al1060-H24 and

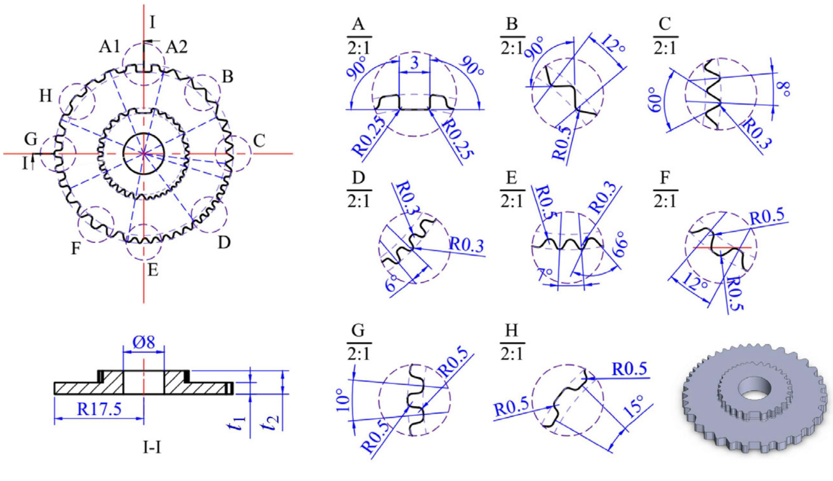

Fig. 2. The detail of the target part.