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Numerical analyses of surface roughness during bending of FCC single crystals and polycrystals

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ABSTRACT

Bending is a common strain path observed in various metal forming operations. In this paper, a rate-dependent crystal plasticity model is incorporated into the commercial software LS-DYNA to analyze the effect of five common Face Centered Cubic (FCC) crystal orientations on the surface roughness developed during bending. Single crystals and polycrystals are modeled and the developed surface roughness is quantified. The models treat single crystals as a range of orientations that lie within 10 degrees of the specified orientation, mimicking the many subgrains that form during the deformation of aluminum single crystal. Polycrystals are treated in the same fashion but instead contain a mix of specified orientations of different texture components of rolled aluminum sheets. Second derivative surface roughness calculations are done both perpendicular and parallel to the bend axis. The simulations reveal that the presence of the Brass and S orientations greatly increases surface roughness. Surface roughness is seen to correlate well with a lack of strain accommodating capability of texture.

1. Introduction

Bending is a common metal forming operation but this simple industrial process subjects the material to a complex strain path compared to simple uniaxial deformation. Certain operations, such as hemming to join outer and inner panels for automotive closures at the edges require bending of the outer sheet metal by as much as 180° to produce sharp hems and subject the sheet metal to large strains at the hem (Zhang et al., 2001). Stamping operations involve different regions of the sheet metal experiencing multiple strain paths and strain reversals in addition to bending strain, which also can be along different bend axes.

Surface roughness on the outer bend surface of a hem is detrimental in various ways. Cosmetically, unpainted surfaces lose their mirror like finish with added surface roughness. Conversely, painted surfaces can develop issues with primer adherence with added surface roughness. From a performance standpoint, fatigue resistance in materials decline with added surface roughness (Yue, 2005) and at extreme levels, surface roughness can trigger localization during forming operations (Becker, 1998). A special case in surface roughness on stamped metal panels, known as "roping", is highly undesirable in automotive body panels. Surface roughness can be linked with a material's crystallographic texture; in other words, changing the texture will change the resultant surface roughness (Dao and Li, 2001). Lefebvre et al. (2012) showed that surface anomalies have large dependence on neighboring grains. The interaction between neighboring grains not only included grains found on the sheet surface, but also included grains located below the surface of the sheet. This conclusion is consistent with the results of Guillotin et al. (2011). The impact of this grain interaction has not been studied for bending loading

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conditions. Groche et al. (2010) as well as Nygards and Gudmundson (2004) discuss the impact of grain size on surface roughness, however this study has chosen to focus on grain orientation effects.

Different techniques have been employed to measure surface roughness. The large impact of surface roughness on friction, lubrication and wear of contacting surfaces has led researchers to study and develop methods for quantifying surface roughness. Many of these methods involve fraction of surface area above or below a given smooth plane parallel to the sample surface in question. Measuring surface roughness is commonly done by tracing a line on the surface of the material and recording the height of the surface along the scan line. By using multiple scan lines, the three-dimensional (3D) surface of the material is constructed. Mathematically, calculating the second derivative of the plots created by the scan lines can provide an instantaneous quantitative measure of the curvature of the surface line (Williams, 2005). By analyzing the spread of the second derivative, the overall surface roughness can be quantified. Unfortunately, experimental surface scan data contains much artificial noise, which interferes with the second derivative calculation. To reduce the amount of noise in the experimental data, filters can be used with moderate success (Schouterden and Lairson, 1996). Another problem with second derivative calculations is that the data resolution can affect the results. For the study presented in this paper, second derivative calculations have been used due to the ease of obtaining trace lines in finite element method (FEM) simulations where there is no experimental noise in the data and every simulation has the same mesh and therefore the same data resolution (Williams, 2005). An advantage to using a measure of curvature for quantifying surface roughness is that it can be directly related to the radius of the surface grooves which in turn helps predicting stress concentrations due to geometrical imperfections. Along with the second derivative roughness quantification a more commonly used root mean square (RMS) is used as well for comparison purposes.

Imperfections in the form of banding (parallel ridges on the surface of the deformed specimen) can also be attributed to localization and failure. The ridges cause localization in the valleys and limit the formability of the material (Becker, 1998). The work of Lefebvre et al. (2012) showed that a crystal plasticity based model could be used to predict the banding effect in ferritic stainless steel sheets. Any insight on the factors that lead to banding can be used to help suppress the formation of banding and provide more versatility to the material being studied. The second derivative surface roughness values along perpendicular scan lines are used to quantify the banding in this study.

Bending has been studied using isotropic material models (Lele and Anand, 2009) as well as anisotropic models (Lee et al., 2012) to study a variety of phenomena such as spring back. However in order to study surface roughness, a distribution of material properties is required to create localized non-uniform deformation. For this reason, a crystal plasticity theory based constitutive model is used for this study.

Surface roughness studies during uniaxial tension have been performed with two-dimensional (2D) models (i.e., Becker, 1998) providing some understanding of the mechanisms responsible for their appearance. However, bending is a relatively more complicated loading condition. While 2D studies using shell elements to model a plane perpendicular to the bend axis have been used in studies to simulate bending (i.e., Kuroda and Tvergaard, 2004; Kuroda and Tvergaard, 2007; Hu et al., 2010), the capability of 2D models to represent accurately the state of strain and stress as well as to reveal the presence of banding is inadequate. Mattei et al. (2013) performed an experimental study on the bending response of aluminum sheet. The results included a linking of surface roughness with localized surface strain however did not give a microstructure based explanation of their observations.

In this paper, the surface roughness that develops during bending in FCC crystals is investigated. Five common orientations (texture components) found in aluminum sheets, Copper, Brass, Cube, Goss, and S1, are employed in the simulations. In order to investigate the effect of crystallographic orientation on the overall surface roughness (of the outer surface of the bent material), bending simulations are performed using both single crystals and polycrystals. First the predictive capabilities of two-dimensional (2D) models are investigated by simulating plane strain tension (for the top layer of the bend). The predicted surface profile by the 2D model is then compared to the surface roughness predicted by the full 3D model. Simulations of surface roughness during bending of single crystals of different orientations using the 3D model are presented. A series of bending simulations with polycrystals containing an equal distribution of only two of the above orientations within the structure are performed and the relative contributions of different orientations to the surface roughness are discussed. Finally simulations of bending are performed in a polycrystal containing all five orientations to gain insight into mitigating any surface roughness concerns during deformation of aluminum sheets undergoing bending mode of deformation.

2. Constitutive model

The polycrystal plasticity model formulated by Asaro and Needleman (1985) and used by Inal et al. (2002) is employed in this analysis. The approach is outlined in Rossiter et al. (2010). Crystallographic slip and elastic lattice distortion are combined to account for total deformation.

The deformation gradient tensor $\boldsymbol{F}$ is written as:

$$\boldsymbol{F} = \boldsymbol{F}^{*}\boldsymbol{F}^{\boldsymbol{p}}, \tag{1}$$

where the crystallographic slip is represented by $\boldsymbol{F}^{p}$, and the elastic deformation and any rigid body rotation are represented by $\boldsymbol{F}^{*}$.