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Computational modelling of material forming processes / Simulation numérique des procédés de mise en forme

Multiscale modelling of asymmetric rolling with an anisotropic constitutive law

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A parametric study is presented, which employs a new anisotropic constitutive law in order to study the influence of anisotropic plasticity on the deformation field of the Asymmetric Rolling (ASR) process. A version of the FACET method is presented, where an analytical yield function is restricted to the subspace of the stress and strain rate space relevant for 2D Finite Element Analysis (FEA), but can still accurately reproduce the plastic anisotropy of an underlying Crystal Plasticity (CP) model. The influence of anisotropy on the deformation field and corresponding texture evolution is examined in terms of the changes in texture component volume fractions and formation of texture gradients. It is found that a material with the anisotropy of a sharp cold-rolled aluminium alloy is more beneficial than that of a recrystallised hot-rolled aluminium alloy, and this influence of anisotropy suggests that Asymmetric Rolling (ASR) may be best carried out in the latest stages of cold rolling.

1. Introduction

1.1. Aluminium alloys for automotive bodywork

Aluminium alloys are recently gaining importance as a versatile material in the drive to reduce emissions and increase fuel efficiency of passenger vehicles. For example, the "Super Light Car" project, sponsored by the European Council For Automotive Research (EUCAR) resulted in a design concept with more than 50% (by weight) of aluminium alloys in an application engineered material approach to vehicle weight reduction [1]; aluminium alloy bodywork has also already been used successfully in some mass-produced vehicles such as the Ford F150. However, one of the difficulties in replacing steel with aluminium alloys in automotive bodywork is their lower formability, which arises in part from their characteristic plastic anisotropy, which in turn is closely related to their crystallographic texture [2].

In general the 5XXX series alloys are employed in inner panels due to their better formability, while the 6XXX series alloys are almost exclusively used for outer panels where formability is to some degree traded for the ability to increase the yield strength after forming by precipitation hardening. Precipitation hardening is crucial to providing the necessary dent resistance [3]. The main alloying elements in the 6000 series alloys, namely Mg and Si, have strong solid-solution, dispersion

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Abbreviations

ODF	Orientation Distribution Function
API	Application Programming Interface
ASR	Asymmetric Rolling
CP	Crystal Plasticity
CPFEM	Crystal Plasticity Finite Element Method
EUCAR	European Council for Automotive Research
FE	Finite Element
FEA	Finite Element Analysis
LDH	Limiting Dome Height
LDR	Limiting Drawing Ratio
ND	Normal Direction
NNLS	Non Negative Least Squares
OIM	Orientation Imaging Microscopy
PSN	Particle Stimulated Nucleation
RD	Rolling Direction
SR	Symmetric Rolling
TBH	Taylor–Bishop–Hill
TD	Transverse Direction
UTS	Ultimate Tensile Strength
XRD	X-Ray Diffraction
CPFFT	Crystal Plasticity Fast Fourier Transform

and precipitation (age) hardening effects. In addition, these elements inhibit recovery, which increases the strain hardening rate [4].

In general, 6016 is currently valued for formability and corrosion resistance, while 6111 is more favoured in the US for its higher Ultimate Tensile Strength (UTS) after ageing, as typically thinner sheet gauges (0.9–1.0 mm) are employed there [3]. While the nominal compositions of these alloys do allow producers some flexibility to adjust the mechanical properties and heat treatability, ultimately quite specific compositions are required to obtain an optimal combination of low-yield strength before forming and high-yield strength after the paint bake cycle [5]. This motivates research into mechanical processing techniques that can improve material properties, such as formability, without altering composition.

1.2. Formability, anisotropy, and texture

The formability of a sheet metal can be quantified by parameters such as Limiting Dome Height (LDH), Limiting Drawing Ratio (LDR), the direction-averaged normal anisotropy $\bar{r}$ and the power-law strain-hardening exponent n. Stress ratio parameters can be similarly employed, e.g., the ratio P of stress in plane strain tension to the equibiaxial stress [6] or the ratio of stress in plane strain tension to the pure shear stress [7]. Anisotropy parameters such as $\bar{r}$ are of particular interest in the current context, as they can be obtained from multiscale models.

Whiteley [8] attributed the discovery of a correlation between LDR and $\bar{r}$ to Lankford et al. [9],[1] presented the first theoretical analysis in the form of Eq. (1), and suggested that LDR was only weakly correlated with n. The validity of this view has since been upheld by experiment and analyses [10]. The correlation may be explained by considering that increasing the value of $\bar{r}$ should generally increase the proportion of strain occurring in the sheet plane rather than in the thickness, so that the thickness is reduced less rapidly during deformation, and failure is inhibited:

$$\mathrm{LDR} = \exp\left(\mathfrak{f}\sqrt{\frac{1+\bar{r}}{2}}\right) \tag{1}$$

The factor $\mathfrak{f}$ in Eq. (1) is a tuning parameter used to account for the effects of friction, punch geometry, and sheet thickness.[2] A more advanced analysis [11] provides Eq. (2), which extends Eq. (1) to include the influence of n on LDR. Eq. (2) predicts that in the range $0.15 \le n \le 0.3$, which accounts for most commercially produced aluminium alloys, LDR is only weakly a function of n, while for fixed values of n the relationship between $\bar{r}$ and LDR is almost linearly increasing. Thus it is reasonable to expect that increasing $\bar{r}$ increases formability in deep drawing:

$$\mathrm{LDR} = \left[\exp\left(2\mathfrak{f}\,\mathrm{e}^{-n}\sqrt{\frac{1+\bar{r}}{2}}\right) + \exp\left(2n\sqrt{\frac{1+\bar{r}}{2}}\right) - 1\right]^{\frac{1}{2}} \tag{2}$$

The anisotropy parameters such as $\bar{r}$ can be determined by mechanical testing, but due to the fact that $\bar{r}$ is a function of the yield surface, it may also be derived numerically from experimental texture measurements by means of a statistical Crystal Plasticity (CP) model [12]. Thus modification of the texture, which in turn results in modification of the yield surface, may be expected to modify $\bar{r}$ and ultimately the formability in deep drawing.

Rolled sheet steels typically feature textures with an α fibre ($\langle 110\rangle \parallel$ Rolling Direction (RD)) and γ fibre ($\langle 111\rangle \parallel$ Normal Direction (ND)); rolled aluminium alloys have quite different textures, typically consisting of the β fibre, (i.e. orientations

[1] I.e. cited by Whiteley [8] as [9].
[2] $\mathfrak{f} = 1.0$ for perfect frictionless cup drawing.