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Enhancing workability in sheet production of high silicon content electrical steel through large shear deformation

Andrew B. Kustas[a,*], David R. Johnson[b], Kevin P. Trumble[b,d], Srinivasan Chandrasekar[c,d]

[a] Material, Physical, and Chemical Sciences Center, Sandia National Laboratories, Albuquerque, NM, 87185, United States
[b] School of Materials Engineering, Purdue University, West Lafayette, IN, 47907, United States
[c] School of Industrial Engineering, Purdue University, West Lafayette, IN, 47907, United States
[d] Center for Materials Processing and Tribology, Purdue University, West Lafayette, IN, 47907, United States

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ABSTRACT

Enhanced workability, as characterized by the magnitude and heterogeneity of accommodated plastic strains during sheet processing, is demonstrated in high Si content Fe-Si alloys containing 4 and 6.5 wt% Si using two single-step, simple-shear deformation techniques – peeling and large strain extrusion machining (LSEM). The model Fe-Si material system was selected for its intrinsically poor material workability, and well-known applications potential in next-generation electric machines. In a comparative study of the deformation characteristics of the shear processes with conventional rolling, two distinct manifestations of workability are observed. For rolling, the relatively diffuse and unconfined deformation zone geometry leads to cracking at low strains, with sheet structures characterized by extensive deformation twinning and banding. Workpiece preheating is required to improve the workability in rolling. In contrast, peeling and LSEM produce continuous sheet at large plastic strains without cracking, the result of more confined deformation geometries that enhances the workability. Peeling, however, results in heterogeneous, shear-banded microstructures, pointing to a second type of workability issue – flow localization – that limits sheet processing. This shear banding is to a large extent facilitated by unrestricted flow at the sheet surface, unavoidable in peeling. With additional confinement of this free surface deformation and appropriately designed deformation zone geometry, LSEM is shown to suppress shear banding, resulting in continuous sheet with homogeneous microstructure. Thus LSEM is shown to produce the greatest enhancement in process workability for producing sheet. These workability findings are explained and discussed based on differences in process mechanics and deformation zone geometry.

1. Introduction

In thermomechanical processing, the workability of the workpiece material, defined here as some combination of the total strain at failure and heterogeneity of the accommodated strain, is an important parameter to consider (Cockcroft and Latham, 1968). Metals and alloys exhibit highly variable degrees of workability that depend critically on the characteristics and mechanics of the processing method employed, in addition to the intrinsic material effects. Strong instances of process-dependent workability can be gleaned from literature when comparing different thermomechanical methods, for example rolling, forging, extrusion, or hydro-forming. In general, processes that impose larger hydrostatic pressure with more confined deformation-induced heating are linked with improving workability of a workpiece material (Cockcroft and Latham, 1968), as demonstrated in the classic works of Bridgman on steels (Bridgman, 1945) and brittle glasses (Bridgman and Šimon, 1953) and more recently in severe plastic deformation techniques (Zehetbauer et al., 2003). For commercial metal working processes, such as sheet rolling, consideration of workability is particularly relevant, where non-uniform strains during deformation negatively impact microstructures and properties of the sheet (Schey, 1980). Metal sheet is processed commercially by rolling through repeated application of small compressive strains through a wide deformation zone that gradually reduce the thickness of a workpiece cross-section. While paramount to large-scale sheet making, rolling has sometimes been shown to impart inhomogeneous microstructures and cause cracking at low strains due to unfavorable deformation zone geometry and insufficient confinement of the deformation. These process-based workability limitations of rolling are particularly important for materials of intrinsically low workability (*e.g.*, Ti and Mg alloys, Fe-Si steels) and overcoming them is therefore essential for improving sheet making from such alloys.

* Corresponding author.
E-mail addresses: akustas@sandia.gov (A.B. Kustas), davidjoh@purdue.edu (D.R. Johnson), driscol@purdue.edu (K.P. Trumble), chandy@purdue.edu (S. Chandrasekar).

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Table 1
Overview of thermomechanical sheet processing methods explored for the Fe-Si alloys.

Process	Deformation Mechanics	Defining Attributes
Rolling	Plane-strain compression, diffuse deformation zone.	Multi-stage; small-strain deformation that incrementally compresses ingots to thin sheet.
Peeling	Plane-strain simple-shear, narrow and unconstrained deformation zone.	Single-step, large-strain deformation; thin sheet produced from ingots by cutting with a sharp tool.
LSEM	Plane-strain simple-shear, narrow and constrained deformation zone.	Single-step, large-strain deformation; thin sheet produced from ingots by a (constrained) hybrid cutting-extrusion process using two tools.

In this study, improved workability – compared to that in conventional rolling – is demonstrated in sheet fabrication of Fe-Si alloys (up to 6.5 wt% Si) using two novel simple-shear processes, peeling (*i.e.*, a form of free cutting) and large strain extrusion machining (LSEM), a hybrid cutting-extrusion process. These processes are shown to enhance the effective workability of Fe-Si (electrical steels) for achieving shape change by virtue of advantageous deformation zone geometries and characteristics. High Si content Fe-Si alloys were selected as model material systems due to their importance in electrical power systems as thin laminated sheet, and for their poor material (unique compositionally-driven) workability in sheet rolling. Additionally, these alloys also encapsulate workability issues that arise in blanking and punching of high-strength steels now being considered for automotive applications.

2. Background

A brief qualitative comparison between rolling and the two simple-shear deformation processes is provided in Table 1. While all three processes are plane-strain (*i.e.*, constant sheet width), each has different fundamental deformation characteristics. In the case of rolling, the deformation zone geometry is such that the straining is significantly more diffuse (*i.e.*, spread wider) than in the simple-shear processes. Hence, the deformation-induced temperature rise is small and much less confined, along with smaller levels of hydrostatic pressure. Furthermore, rolling is limited in terms of the amount of strain that can be imposed in each step, requiring multi-stage reductions of ingot material to obtain thin sheet cross-sections. In contrast, the two shear processes impose large shear strains over a narrow deformation zone in a single step, with substantial temperature rise due to the plastic deformation-induced heating. The strain imposed is independent of the sheet thickness, and a larger level of hydrostatic pressure prevails in the deformation zone. It is these attributes of the deformation that are favorable for enhancing the workability. Since the deformation characteristics of rolling and the simple-shear processes are vastly different and impart unique responses in materials, a brief review of the underlying mechanics of each of these processes is provided in Sections 2.1 and 2.2. A synopsis of the technological importance and composition-based workability issues of the model Fe-Si alloys is then given in Section 2.3.

2.1. Flat sheet rolling

Metal ingots are typically processed into sheet and foil forms by rolling. This involves multiple steps of hot and cold rolling reductions with intermediate annealing to achieve the final desired sheet/foil thickness (Cockcroft and Latham, 1968). The sheet rolling deformation is plane-strain compression, with the amount of imposed (effective) strain being a function of the thickness reduction (r), according to:

$$\varepsilon = \frac{2}{\sqrt{3}} \ln\left(\frac{1}{1-r}\right) \quad (1)$$

While flat rolling has outstanding advantages for continuous processing of large volume of sheet, there are a few key disadvantages. These include the multiple processing steps entailing expansive infrastructure and energy costs, inhomogeneous deformation, limited control of crystallographic texture in the sheet, and a difficulty/inability to process alloys with intrinsically low material workability (Kustas et al., 2016a,b).

In producing sheet from alloys of low material workability, rolling has encountered challenges. One issue is the crystallographic textures that naturally develop from the plane-strain compression deformation. Sheet tend to develop in-plane crystal orientations with the slip planes aligned perpendicular to the surface normal and slip directions along the rolling direction. Such textures can hinder processing of metals in additional rolling passes. A noteworthy example of this is in rolling of HCP crystal structures, where basal textures, with characteristically low formability, develop that promote cracking. In addition, rolling has limitations in the amount (and confinement) of deformation-induced heating and hydrostatic pressure imposed in the deformation zone. Hydrostatic pressure (p), in particular, is important because it can significantly enhance the ductility and workability of metals during deformation, as outlined in Cockcroft and Latham (1968). In rolling, p in the deformation zone is approximately equal to the shear strength (k) of the metal; this value is significantly smaller than in the simple-shear deformation processes (Section 2.2). This process limitation in rolling will be demonstrated experimentally.

2.2. Simple-shear deformation

Simple-shear deformation is an attractive alternative to rolling for processing metals into sheet. Two machining-based processes (Fig. 1) have been explored recently on Mg alloys by Efe et al. (2012) and on Fe-Si alloys by Kustas et al. (2016a,b). The first process (Fig. 1a), referred to as peeling (or free machining), is a single-step shear deformation process that utilizes a sharp, wedge-shaped cutting tool to remove, *i.e.*, peel away, thin cross-sections (initial thickness, t_o) of material from a rotating workpiece with constant surface velocity (V_o). The peeled material, *i.e.*, the chip, represents the sheet. In general, this sheet is characterized by one somewhat rough (serrated) surface, the free back surface of the chip, and another smooth surface, the chip surface in contact with the tool face. Due to the serration, the final sheet thickness (t_c) has some positional variability. The extent of the serration decreases, and can even disappear, with increasing tool rake angle (α). The sheet formation itself occurs by simple-shear confined to a narrow deformation zone (thickness $\sim 100\,\mu m$), with large strains (effective strains, $\varepsilon > 1$) being imposed at high strain rates ($\sim 10^3\,s^{-1}$). This local imposition of the shear deformation, and typically large V_o (> 1 m/s), results in a significant temperature rise in the deformation zone (near-adiabatic heating) where the shape transformation into sheet is occurring. The effective strain in peeling, as discussed by Efe et al. (2012), can be estimated through:

$$\varepsilon = \frac{1}{\sqrt{3}}\left(\frac{\lambda}{\cos\alpha} + \frac{1}{\lambda\cos\alpha} - 2\tan\alpha\right) \quad (2)$$

where $\lambda = t_c/t_o$ is the chip thickness ratio (*i.e.*, final sheet (chip) thickness to the initial uncut thickness) and α is the cutting tool rake angle. In contrast to rolling, the large strain in peeling is imposed in a single processing step and is independent of the sheet dimensions. Furthermore, due to the deformation geometry, the hydrostatic pressure is also significantly larger than in rolling. Based on slip-line field analysis by Efe et al. (2012), $p \sim 2k$ and nominally a function of the λ