Deformation and recrystallization texture development in Fe-4%Si subjected to large shear deformation

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Abstract – Machining is used as a deformation technique to impose large shear strains ($\gamma \sim 2$) in a commercial Fe-4%Si alloy. The partial $\langle 111 \rangle$ and $\{110\}$ – fiber texture components are generated throughout the as-deformed microstructure, which is expected of BCC metals deformed in simple shear. Using an annealing schedule similar to that in the commercial rolling process, samples retain the deformation texture, consistent with a continuous-type recrystallization mechanism. Fine-grained annealed samples reveal two different partial fiber orientations, one of which becomes the dominate texture, following the high-temperature growth treatment. The mechanisms of texture evolution and implications for texture control in the machining-based process are discussed.

Introduction

Silicon iron (Fe-Si) sheet is commonly used in transformer applications for its intrinsic magnetic properties, which are routinely achieved through multistep hot and cold rolling involving precise control of both deformation and annealing stages. Texture evolution of the thin Fe-Si sheet throughout the different stages in conventional processing has been well documented, with special interest regarding the development of the Goss texture \cite{1}; however there has been limited evaluation of texture development in Fe-Si under deformation techniques other than rolling. The focus of this paper is to evaluate the texture evolution of Fe-4%Si following large shear deformation from machining.

Background

Machining is a technique that removes material through cutting, by using a sharp wedge tool set at a preset depth ($t_o$) into the bulk (Fig. 1). As a result of intense local shear (simple shear) deformation imparted by the cutting tool, material is removed from the surface of the rotating workpiece in the form a continuous chip/strip. This intense shear deformation occurs within a narrow zone, capable of creating a refined microstructure in the strip \cite{2}. Furthermore, high cutting speeds can be used to produce large, local temperature rises from adiabatic heating.

To model the deformation zone, a single shear plane is often used, which allows for analysis of the imposed shear strain during cutting. Estimates of the shear strain ($\gamma$) can then be made from measurements of the chip thickness ratio ($\lambda = t_c/t_o$) and tool rake angle ($\alpha$). In addition to control of the magnitude of the shear strain, $\alpha$ also controls the strain path as defined, for example, by the shear plane angle $\phi = 90^\circ + \alpha - \phi$ where $\phi = \tan^{-1}(\cos \alpha/(\lambda-\sin \alpha))$. Both strain path and slip system activity are known to control texture evolution during deformation \cite{3}. In BCC systems, the $\{110\} <111>$ slip
system is most commonly activated; consequentially the slip plane and direction are expected to align with the macroscopic shear plane.

**Experimental**

A nominal Fe-4%Si plate (Scientific Alloys Inc, RI) was used as the bulk workpiece (actual analysis, wt%: Fe-3.83Si-0.32Mn-0.028P-0.018P-0.015S-0.006Al). The as-received hot-rolled plate possessed an initial coarse grain microstructure ($d \sim 1$ mm), which was refined through cold-rolling ($r = 62\%$) and annealing to obtain a finer grain size of $\sim 20$ μm. A 10-cm diameter disk workpiece was removed from the plate with a final thickness of 0.32 cm, which corresponds to the width for the cut strip samples. Cuts were made using a cemented carbide cutting tool under a single rake angle ($\alpha = 20^\circ$), at a constant surface velocity ($V_s = 2$ m/s) resulting in a shear strain of $\sim 2$ in strips $\sim 250$ μm thick ($t_c$). Strip samples were subjected to a low-temperature open-air anneal at 700 °C for 30 min followed by a high-temperature anneal at 1100 °C for 5h in a controlled atmosphere of Ar-5%H$_2$ flowing at $\sim 1$ cm$^3$/s at 1 atm. These conditions were selected to mimic commercial annealing. Texture measurements were conducted through electron backscatter diffraction in an FEI XL-40 field emission SEM. Data were analyzed using EDAX OIM software and processed through a confidence index (CI) filter ensuring a minimum CI value of 0.1 was achieved for each data point.

**Results and discussion**

As-deformed chip samples revealed a microstructure possessing grains aligned in the shear direction with a serrated top surface and a smooth bottom surface, which shows additional secondary shear deformation (Fig. 2). The axes used for pole figures were the rake face normal (RFN) and chip flow direction (CFD), which provided a convenient way to analyze texture components. Black regions in the inverse pole figure color map indicated areas that were severely deformed and consequentially produced low signal. Additionally, blurred grain boundaries were present, expected from microstructures containing high dislocation density [4]. Analysis of the as-deformed chips revealed a simple shear texture characterized by the partial {110} and <111> - fibers aligned with the shear plane and shear direction, respectively. These partial fibers have been observed by others using similar shear-based deformation techniques [5]. For the selected deformation condition, the measured textures were aligned at an angle $\phi' \sim 78^\circ$, which is close to the theoretical value from the shear plane model ($\phi' \sim 81^\circ$).

**Figure 2** – As-deformed side view of the chip microstructure with dotted line illustrating the secondary shear zone. Inverse pole figure color map from the bulk showing inclined, elongated grain structure and corresponding (110) pole figure with ideal simple shear partial fibers (dotted lines) superimposed.

Following the low-temperature anneal, a fully recrystallized microstructure was achieved with grain size $d \sim 20$ μm (Fig. 3). Pole figures from the bulk indicated the deformation texture was retained following annealing. Additional scans near the chip rake face also showed the same fiber components but at significantly lower orientation ($\phi' \sim 39^\circ$) than in the bulk of the chip, consistent with secondary shear effects at the material/tool interface during cutting.
Figure 3 – Pole figures from the bulk (left) and secondary shear zone (right) for the low-temperature anneal condition. Textures indicate the simple shear fibers are retained following annealing.

The high-temperature (growth) annealing treatment resulted in significant grain growth ($d \sim 100 - 200 \mu m$) with 1 to 2 grains through the thickness of the strips (Fig. 4). Texture measurements indicated grains from the bulk of the strips consumed those within the secondary shear zone. This result is evident from the $45^\circ$ slices of the ODFs for the low – and high-temperature annealed bulk (Fig. 4).

Figure 4 – Coarse grains that grew in the high-temperature annealing treatment. ODF sections for the bulk chip following low-temperature annealing (left) and the high-temperature growth treatment (right) showed strong intensity peaks at nearly identical Euler angles, indicating similar texture components were present. Note, ODF sections were generated from several grains.

The similarity between the deformation and recrystallization textures following large shear deformation has been observed in other systems in the literature [6, 7]. In general, it has been proposed that large strains imposed during deformation result in the formation of complex microstructures with non-equilibrium, high-angle sub-boundaries. Upon annealing, recovery initially transforms these boundaries into conventional grain boundaries, at which point homogeneous grain growth commences [8]. This process has been classified as continuous recrystallization (cRX). Since such a substructure was expected from the large strains experienced during machining, it is believed that the traditional inhomogeneous nucleation and growth of grains commonly observed in discontinuous recrystallization (dRX) was limited here, in favor of the cRX mechanism. Therefore, a recrystallization texture was not developed in a traditional sense and the same deformation texture was retained following annealing.
The homogeneous nature of cRX was confirmed experimentally from incremental annealing at 700 °C at times as low as 20 s (not shown).

After the high-temperature treatment, grains in the secondary shear zone were consumed by grains in the bulk due to the relative size advantage possessed by the bulk grains (d ~ 21 µm) over the grains within the secondary shear zone (d ~ 14 µm) following the low-temperature anneal. The finer size of the grains in the secondary shear zone is consistent with the additional deformation imposed from friction at the rake face, which provided a finer starting deformation sub-structure for grain coarsening. As a whole, machining results in a fundamentally different texture when compared with conventional rolling of Fe-Si, which is a product of the differences in the two deformation processes. For commercial sheet production, a hot rolled plate is subjected to multiple rounds of large cold rolling reductions with intermediate annealing. The first round of rolling leads to an inhomogeneous texture throughout the cold rolled sheet thickness, with texture components varying at the sheet surface, mid-plane and intermediate regions [1]. Machining brings about a nearly homogeneous texture regardless of the starting plate texture. Furthermore, the orientation, in contrast to rolling, can be varied as a function of α to engineer a wide variety of partial fiber orientations with respect to their inclination relative to the CFD. In rolling, a different recrystallization texture is produced when compared to machining. This annealed texture provides the essential environment for Goss grains to grow abnormally in the commercial grain-oriented sheet. As a consequence of the inclined orientations afforded by machining, a different microstructural environment may be induced around Goss grains in the machined strip, allowing for evaluation of the abnormal growth mechanisms in a new manner.

Summary

Machining, as a model simple-shear deformation technique, was used to produce chips from an Fe-4%Si alloy plate. Following machining, a classic simple shear type deformation texture developed defined by two partial fibers. This texture was retained following both a low-temperature and subsequent high-temperature annealing treatment. Texture conservation is believed to result from a continuous recrystallization mechanism for the low-temperature anneal while a size advantage offers an explanation for the mechanism behind the loss of the secondary shear zone following the high temperature growth treatment. Taken as a whole, shear deformation provides unconventional texture components and texture control when compared with current commercial processing for Fe-Si based on multistep rolling.

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