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The effect of constrained groove pressing on grain size, dislocation density and electrical resistivity of low carbon steel

F. Khodabakhshi, M. Kazeminezhad *

Department of Materials Science and Engineering, Sharif University of Technology, Azadi Ave., Tehran, Iran

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ABSTRACT

In this research, constrained groove pressing (CGP) technique is used for imposing severe plastic deformation (SPD) on the low carbon steel sheets. Using transmission electron microscopy (TEM), X-ray diffraction (XRD) and optical microscopy, the microstructural characteristics of produced sheets are investigated. The results show that CGP process can effectively refine the coarse-grained structure to an ultrafine grain range. Dislocation densities of the ultrafine grained low carbon steel sheets are quantitatively calculated and it is found that the CGP can effectively enhance the dislocation density of the sheets. Measurements of their electrical resistivity values show that microstructure refinement and increasing the dislocation density can efficiently increase the electrical resistivity of the CGPed sheets up to ~100%.

1. Introduction

Microstructure of materials can greatly affect their mechanical and physical properties such as hardness, strength, electrical resistivity, thermal conductivity, and magnetic properties. Many works have been carried out [1–4] on the relationship between microstructure and physical properties for different materials. Recently, nano-structured (NS) materials have been mostly attracted in materials science due to their unique properties and behavior. These materials are defined as solids having microstructure features in the range of nanometer, at least in one dimension [5]. Two complementary approaches have been developed to synthesize NS solids. The first is the "bottom–up" approach in which bulk NS materials are assembled from individual atoms or nano-scaled blocks such as nano-particles. The second approach is the "top-down" approach in which existing coarse-grained materials are processed to produce nano-structured materials. The most successful "top–down" approach involves the use of severe plastic deformation in which materials are subjected to the very large strains without changes in the cross-sectional dimensions of the samples [6,7]. The principle of SPD processes includes increasing the dislocation density by heavily uniform deformation, forming of dense dislocation walls and acquiring ultrafined or nano-scaled microstructure [8]. There are many researches on producing NS materials using SPD and their mechanical properties. But, limited works have been done on the variations of physical properties due to severe plastic deformation [9] and therefore, it seems that more works should be carried out to investigate the relationship between microstructure evolution due to SPD and changes in physical properties. Electrical resistivity is one of the most important physical properties because its measurement is easy and also, it represents the variations of many other physical properties such as electrical and thermal conductivity. Also, the electrical resistivity has been used in many researches as a tool for determining the microstructural phenomenon occurs in different processes. Previous researches show that the grain size is decreased and the dislocation density is significantly increased through SPD of metals [6,7]. Also, it has been shown that a smaller grain size leads to lower thermal conductivity and higher electrical resistivity due to enhanced phonon boundary scattering at interfaces and crystal imperfections such as dislocations [10]. It has been shown that the electrical resistivity of a copper superconductor is mainly dependent on the surface of grain boundaries and concentration of second phase precipitations [11]. Since microstructure is refined during SPD and microstructural evolution can affect the electrical resistivity changes, therefore, it seems that an investigation into the effect of SPD on electrical resistivity is very interesting and important.

Refining the grain size of useful metals such as low carbon steel by SPD method is of great interest as the yield stress is significantly increased. This leads to an improvement in the strength to weight ratio, which is a desirable property for automobile industry. Also, measuring the electrical resistivity changes of low carbon steel sheets as a result of SPD process is very important. Among SPD methods that are now available [7,12–19], two major processes that applicable for sheets are accumulative roll bonding (ARB)

* Corresponding author. Tel.: +98 21 66165227; fax: +98 21 66005717.
E-mail address: mkazemi@sharif.edu (M. Kazeminezhad).

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and constrained groove pressing. The process of ARB was invented by Saito et al. [20,21], involves repetitive bonding between two rolled plates and if perfect bonding is not accomplished, the bonding interface may reduce the mechanical properties of the products. Thus, ARB is less considered feasible for severe plastic deformation of sheet metals. Constrained groove pressing for severe plastic deformation was initially proposed by Shin et al. [18]. The principle of groove pressing (GP) is that a material is subjected to repetitive shear deformation under plastic strain deformation condition by utilizing alternate pressings with asymmetrically grooved dies and flat dies. As can be seen in Fig. 1, the groove pressing is carried out such that the gap between the upper die and lower die is the same as the sample thickness and therefore the inclined region of the sample is subjected to pure shear deformation under plane strain deformation condition [8]. Since this method has been recently invented, there are not many works on it and more works should be carried out to examine the evolution of microstructure and mechanical properties of metals during this process. Also, since the SPD of low carbon steel sheet is important and ARB has some disadvantages, in this study CGP method is used for imposing the severe plastic deformation on the low carbon steel sheets.

In the previous work [22], mechanical properties improvement of low carbon steel sheets subjected to CGP have been investigated and it has been shown that this method can effectively increase the strength and hardness of sheets. But, microstructure and some physical properties such as electrical resistivity of low carbon steel sheets during CGP process require more investigations.

In the present study, strains from 0 to 4.64 (each CGP pass imposes strain magnitude of 1.16) are imposed to the low carbon sheets in order to produce a high strength nano-structured sheet. Then, the microstructural characteristics of produced sheets are investigated using XRD, TEM, and optical observations. XRD is employed to determine the grain size and to monitor the microstructural changes during SPD processes and TEM is used for verifying the XRD results. The dislocation density of as-pressed sheets after each CGP pass is calculated from mechanical behavior of sheets. Also, the effect of imposing strain on the electrical resistivity is investigated using standard 4-point probe technique at room temperature.

2. Material and methods

In this research, as-received low carbon steel sheets with dimension of 84 mm × 45 mm × 3 mm were used to study the effects of CGP process on grain refining and variation of electrical resistivity. The chemical composition of this steel is shown in Table 1. Schematic of CGP dies are shown in Fig. 1. One pass of CGP that includes four pressing stages is shown in Fig. 2 (stages 1–4). The pressings are performed such that the gap between the upper die and the lower die is the same as the sample thickness, resulting in pure shear deformation under plane strain condition at inclined regions of the sample. Once the work piece is pressed between the grooved dies, under plane strain condition, an effective strain of 0.58 is imposed to the inclined regions while the flat areas undergo no deformation (Fig. 1(stage 1)). Then the work piece is removed from the dies and is flattened by a set of flat dies, resulting in another 0.58 effective strain in reverse direction which ends up in 1.16 strain for the deformed regions (Fig. 1(stage 2)). After the straightening, the specimen is rotated 180° around the axis perpendicular to the plane of the sheet which ensures that the subsequent groove pressing (Fig. 1(stage 3)) and straightening (Fig. 1(stage 4)) impose an overall strain of 1.16 to the undeformed regions. Then, a uniform strain of 1.16 has been imposed on the specimen. In this study, Teflon layers that introduced in previous works [22,23] were used as lubricant between low carbon steel sheet and dies. Using the Teflon layers leads to impose the strain magnitude of 4.64 on the low carbon steel sheets through four passes.

The microstructures of deformed sheets after CGP were investigated using optical microscopy, X-ray diffraction and transmission electron microscopy. In order to examine the microstructure with optical microscopy, the as-received sample was selected from the surface plane of specimen. For optical microscopy, samples were ground on papers, polished and then etched in a solution of CH_3OH containing 3% HNO_3.

Table 1
Chemical composition of low carbon steel sheet (wt.%).

Fe	C	Si	Mn	P	S	Cr	Ni	Mo
Base	0.0527	0.0229	0.203	0.006	0.0031	0.0088	0.0281	0.0024

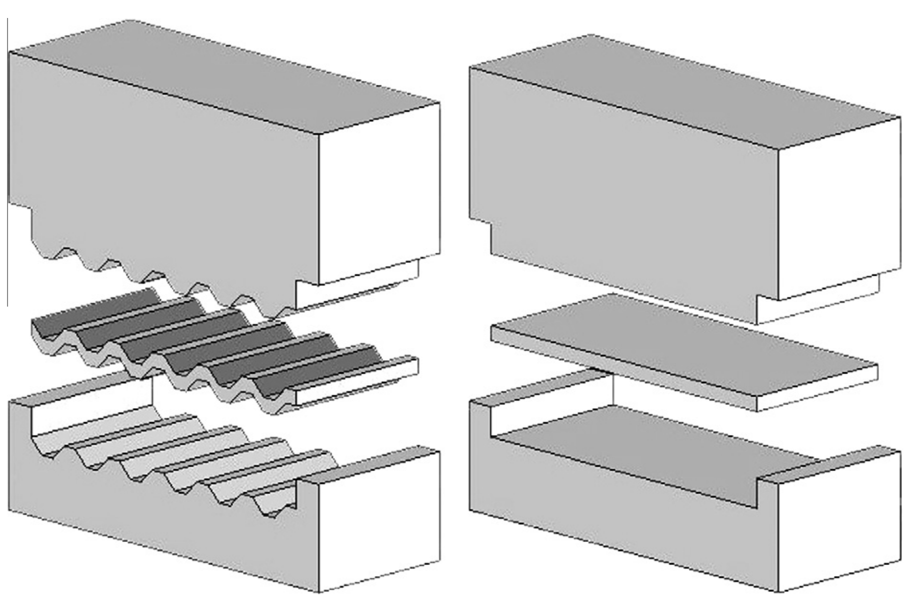

Fig. 1. Schematic of dies used through CGP process, left: grooving die, right: flattening die.