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A study on nanoscale gradient alloying induced by a punching deformation process on low carbon steel

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ABSTRACT

The gradient alloying surface produced on a low-carbon steel material by a punching deformation and recovery process is investigated using scanning electron microscopy, energy disperse spectroscopy and X-ray diffraction. The mechanical properties of the gradient alloying surface are studied using nanoindentation and microhardness testers. The surface layer is observed to contain a $(Fe,Cr)_7C_3$ phase. There is also a decrease in Cr content as grain size increases from the top surface to the matrix. These results can be attributed to defects in the microstructure induced by the punching deformation process, which promote diffusion of Cr in the matrix. The gradient alloying surface also exhibited increased hardness due to the grain refining process, the Cr solution used and the presence of the hard $(Fe,Cr)_7C_3$ phase.

1. Introduction

The gradient alloying surface can be formed by severe plastic deformation and is characterized by multi-scale or multi-gradient changes in both the chemical composition and microstructure. This alloying process has proven to be a promising technique for surface modification. Current deformation methods include surface mechanical attrition treatment (SMAT) [1], ultrasonic or high-energy shot peening [2], sand blasting [3], and mechanical punching [4]. These methods have previously been employed to successfully prepare alloying surfaces. For example, SMAT has been used to accelerate diffusion of Zn, allowing for the formation of an intermetallic compound on the surface of Fe-based alloys [5]. SMAT can also increase the diffusion coefficient of Ni by a factor of approximately two on the surface of pure Cu within a distance of 10 μm [6]. Ultrasonic shot peening has also been used to prepare a Fe–Ni intermetallic compound with a diameter of 2 μm on the surface of Fe-based alloys [7,8].

Our previous work [4] has demonstrated that punching deformation can produce a nanoscale gradient surface on a cupronickel alloy. Compared to other surface deformation methods, punching deformation provides the advantage of a thicker gradient layer. Using a combination of punching, sandblasting and recovery treatment, an alloying surface with a depth of 120 μm containing Al_2Ti and a rich Ti phase (or Al_xTi_y) can be produced on an Al alloy [9]. This method can also be used to prepare a nanoscale alloying layer on stainless steel that contains an Ag phase [10]. From these studies, it is apparent that there are two kinds of deformation processes involved when using this method. However, it remains difficult to identify which process plays a more critical role in the production of the alloying surface. Furthermore, the operation of this method is complex.

Therefore, we chose to investigate the production of gradient alloys using the deformation process alone. The aim of this study is to demonstrate the effectiveness of producing a gradient alloying surface using only mechanical punching deformation on low carbon steel with metallic Cr as an alloying element.

2. Experimental

Samples were cut from a commercial 20 steel ingot (Chinese industrial standard), consisting of (in wt%): 0.2% C, 0.28% Si, 0.50% Mn, 0.1% Cr, 0.14% Ni and 0.12% Cu. The samples were all 30 mm in diameter and 20 mm in length. The samples were ground using SiC paper up to 800-grit. The sample surface was covered with a layer (~1.0 mm thickness) of Cr powder(99.9 wt%, particle size ~75 μm) before being punched for 60 min using a roto-hammer (Bosch Tool corporation) at a frequency of 50 Hz. The head of the punching hammer had a semi-spherical shape that was 3 mm in diameter and scanned the target surface in order to punch it at

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different locations. The punching energy was 1.6 ft-lbs (2.207 Nm). Afterwards the punched sample was recovered at 500 °C under argon for 2 h. Before being characterized and tested, the treated samples were polished using 0.05 μm alumina powder and etched slightly using 4 wt% HNO_3 solution.

The microstructure and chemical composition of each sample were analyzed using as scanning electron microscope (SEM, JSM-6360LV) equipped with energy disperse spectroscopy (EDS, Genesis 2000xms60). The grain size was determined using an atomic force microscope (AFM, Digital Instruments). The phases were analyzed using X-ray diffraction (XRD, UltimaIV). The indentation load–displacement curves at various depths from the top surface were recorded using a nanoindentation tester (Agilent G200) under a maximum load of 50 mN. The microhardness from the surface to the matrix was also measured using a microhardness tester (FM-200) under a load of 50 N.

3. Results and discussion

3.1. Formation of the gradient alloying surface

A typical cross-section of the 20 steel surface after the punching deformation and recovery treatment process is shown in Fig. 1. Results indicate that there is a gradient microstructure on the sample surface based on the range in grain size from nanoscale to microscale (Fig. 1b). As shown in Fig. 1b, the average grain size is also observed to increase gradually from approximately 75 nm at the top surface to about 100 nm at a depth of 120 μm. The grain size further increases to approximately 400 nm between the depths of 120 and 200 μm. At a depth greater than 200 μm, there is a typical deformation microstructure characterized by fibrous grain. The thickness of the overall deformed layer is ~500 μm. It is worth mentioning that this gradient microstructure is similar with those previously observed in samples formed by SMGT [11] and severe plasticity roller burnishing [12]. The punching deformation process involves repeated multidirectional mechanical strikes onto the material surface at high speeds. This generates a gradient

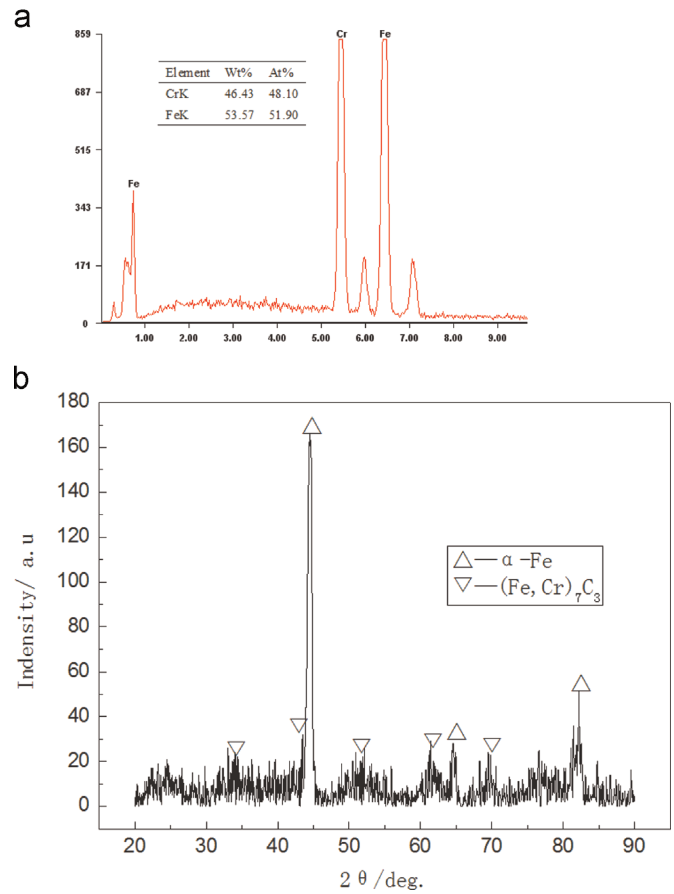

Fig. 2. The EDS of the gray domains (a) and the XRD of the gradient alloying surface (b).

plastic deformation that results in a gradient microstructure. These results are in good agreement with our previous study of surface nanocrystallized cupronickel obtained using this punching

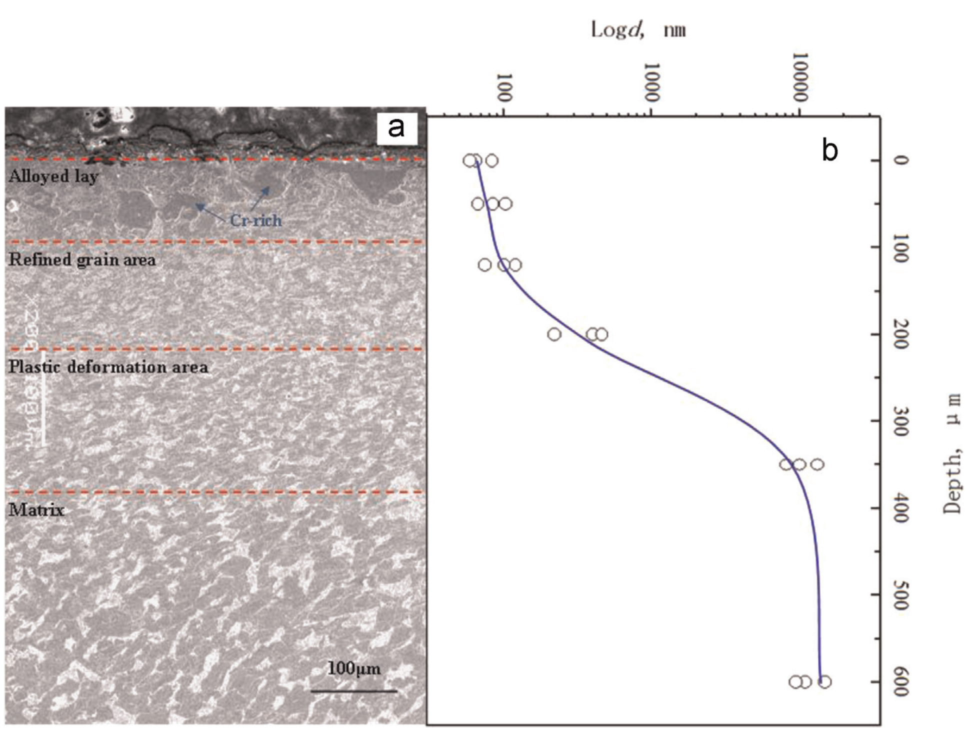

Fig. 1. The SEM image (a), and grain sizes (b) of a cross-sectional surface. The gray domains indicate Cr-rich phases.