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Effect of stress-temperature coupling on gradient alloying induced by punching severe deformation

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ABSTRACT

The effect of stress and temperature coupling on gradient alloyed surfaces induced by punching severe deformation has been investigated by scanning electron microscopy, energy dispersive spectroscopy, X-ray diffraction and microhardness tests. The stress field and temperature field were simulated using the Abaqus finite element method. The results show that surfaces experiencing the stress and temperature coupling effect have a greater depth of the alloying layer and a finer grain. In particular, the level of alloying, as determined by parameters such as the solid solubility of Cr atoms in a Fe crystal lattice and the quantity of the compound $(Fe, Cr)_7C_3$, is significantly increased. These differences are attributed to the coupling effect of stress and temperature, which can increase the number of crystal defects and the metallic Cr diffusion coefficient. Punching deformation without cooling treatment produces a higher hardness when compared to punching deformation with cooling treatment; without cooling treatment the hardness gradually decreases from 295 Hv at the top surface to 185 Hv in the matrix.

1.. Introduction

The failures in metallic work piece always begin at the surface via mechanisms such as fatigue, wear, corrosion and oxidation, all of which can be significantly reduced by gradient alloying induced by surface severe deformation [1–3]. A gradient alloyed surface is characterized by multi-scale or multi-gradient changes in both the chemical composition and microstructure of the material, and gradient alloying is a promising technique for surface modification to reduce failure mechanisms. Current surface severe deformation methods, such as mechanical attrition treatment [4], ultrasonic or high-energy shot peening [5], sand blasting [6], and mechanical punching [7], have been employed to successfully prepare gradient alloyed surfaces. For example, ultrasonic shot peening has been used to prepare a Fe–Ni intermetallic compound with a diameter of 2 μm on the surface of Fe-based alloys [8]. Our previous studies [9–10] have demonstrated that punching deformation can produce a nanoscale gradient alloyed surface on Al2024 alloy and stainless steel. It is known that stress is the main cause of changes in the surface microstructure during surface severe deformation [11]. However, it is inevitable that the increasing stress will result in increasing temperature. Thus far, there are no studies on the effect of temperature on gradient alloying during surface severe deformation. It is well known that the increasing temperature induced by stress can help to increase the diffusion driving force, and thus increase the diffusion velocity. The effect of temperature on gradient alloying induced by surface severe deformation should be further studied, as it will enable further refining of these techniques. In particular, the coupling effect of stress and temperature is more complicated than that of stress alone in gradient alloying during surface severe deformation.

In this study, we demonstrate the difference in microstructure and properties between gradient alloyed surfaces with and without temperature effects. Gradient alloying was applied to target surfaces by punching severe deformation. The samples for gradient alloying were divided into two groups: one experienced the punching process with a cooling treatment and so experienced stress effects only, and the other experienced the punching process, which resulted in stress and temperature effects. Gradient microstructure; element and phase distribution; hardness; stress field and temperature field were evaluated and compared between these sets of samples in order to determine the effects of the combination of stress and temperature on gradient alloying.

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2.. Experimental details

Samples were cut from commercial low carbon steel, 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 surfaces were covered with a layer about 1.0 mm thick of Cr powder (99.9 wt.%, particle size ~75 μm) and then 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 different locations. The punching energy was 1.6 ft-lbs (2.207 Nm). Fig. 1 schematically illustrates a punching process, during which the punching head scans the target surface to punch it at different locations. The repeated punching results in accumulated plastic deformation. The process was well controlled in order to have the entire sample surface punched homogeneously. The punched surfaces had their roughness in the range of 10 μm. In order to decrease temperature effects induced by stress on the alloying process, the sample was immersed in water during the punching process. After punching, the samples were 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 slightly etched using a 4wt.% HNO_3 solution.

The microstructure and chemical composition of the gradient alloying layer were observed with optical microscope (Olympus) and scanning electron microscope (JSM-6360LV) equipped with an energy disperse spectroscopy (GENESIS2000XMS60). The morphology and grain size were determined using an atomic force microscope (Digital Instruments USA). The phases were analyzed using an X-ray diffraction (UltimaIV Japan). Microhardness in cross section from surface to matrix was measured using a microhardness tester (FM-200, USA) under load of 50N. FEM analyses were carried out using the finite element code Abaqus in a 3D space using sample geometrical symmetry conditions. The analysis type used was 3D stress analysis with C3D8 elements for specimen. The material for each simulation was modeled taking into account its strain hardening behavior. The mesh was refined enough to have both good information and shorter CPU times. The poisson ratio, thermal conductivity, specific heat, liner thermal expansion coefficient were 0.3, 46.4 W/(m^2 K), 502.4 J(kg K), 10.6–12.2 × 10^{-6}, respectively.

3. Results

3.1. Microstructure

Fig. 2 present the typical cross-sectional images of a regularly punched sample and a punched sample with cooling. Fig. 3 shows grain size as a function of depth for both samples. It is found that there is a gradient in the microstructure from the surface to the matrix based on the range in grain sizes from nanoscale to microscale. For the sample that experienced punching deformation with no cooling, there is an approximately 125 μm thick region of nanosized grains with random crystallographic orientations. The average grain size increases gradually from about 75 nm at the top surface to about 100 nm at 125 μm depth. The grain size further increases to approximately 12.5 μm from a depth of 125 μm–400 μm. Deeper than 400 μm, there is a typical deformation microstructure characterized by fibrous grains. The thickness of the entire deformed region is around 500 μm. For the sample that experienced punching deformation with cooling, however, the layer of refined grains is only ~325 μm thick rather than 400 μm. The average grain size increases gradually from 105 nm at the top surface to about 12.5 μm at a depth of 325 μm. Beyond 325 μm, there is a typical deformation microstructure. In comparison with the sample experiencing punching deformation with cooling treatment, the sample experienced punching deformation without the cooling treatment has a finer grain size in the top layer, and greater depth of the refined grain layer and the deformation layer.

The cross-sectional distribution of chromium was measured using area scans by EDS, as shown in Fig. 4. This shows that the two punching methods both show decreasing chromium content with distance from the top surface. The total chromium content of the sample experiencing regular punching deformation is greater than that of the sample that experienced punching deformation with the cooling treatment. This is because the chromium distribution in the top layer is much denser and the chromium region has greater

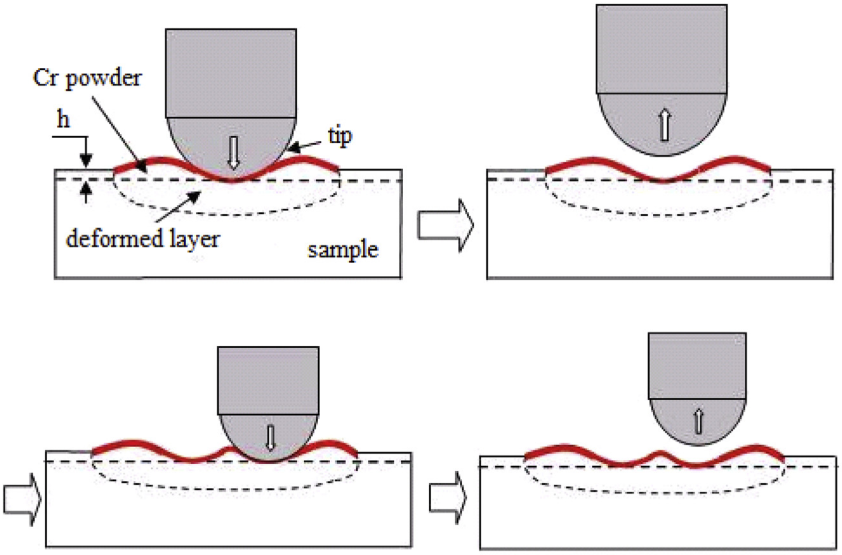

Fig. 1. Schematic illustration of a punching process: the tip was moved up and down at a frequency to impact a target surface and introduced severe plastic deformation in the surface layer.