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Experimental study of the microstructure and stress state of shot peened and surface mechanical attrition treated nickel alloys

Angel L. Ortiz,[a] Jia-Wan Tian,[b] Leon L. Shaw[c,*] and Peter K. Liaw[b]

[a]*Departamento de Ingeniería Mecánica, Energética y de los Materiales, Universidad de Extremadura, 06071 Badajoz, Spain*
[b]*Department of Materials Science and Engineering, University of Tennessee, Knoxville, TN, USA*
[c]*Department of Chemical, Materials and Biomolecular Engineering, University of Connecticut, Storrs, CT, USA*

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The efficacies of shot peening (SP) and surface mechanical attrition treatment (SMAT) in inducing multiple changes in the microstructure and stress state of the workpiece are compared experimentally, for the first time, using depth-profile X-ray diffractometry. SMAT generates a thicker nanocrystalline surface layer, a deeper plastically deformed zone and a thicker surface region with larger residual compressive stresses than SP. These results can have important implications for improving the fatigue life and wear resistance of metals in the future.

Keywords: Surface mechanical attrition treatment; Shot peening; Microstructure; Residual Stresses; X-ray diffractometry

Surface plastic deformation processes have become extensively used by industry to produce metallic components with engineered surfaces and superior mechanical properties (especially fatigue and wear resistance) [1–12]. Shot peening (SP) has doubtlessly been the most popular of these processes to date, and the one adopted generally by industry due to its versatility in treating components of complex geometries. In the SP method, a stream of spherical shots with sizes in the range 0.25–1 mm is blasted against the workpiece at impact velocities in the interval 20–150 m s^{-1}, under a controlled atmosphere [13]. The repeated impacts confer residual compressive stresses and work hardening to the surface region of the workpiece [1–3], but unfortunately do not always induce surface nanocrystallization [1–3,13].

Recently, a new family of surface severe plastic deformation processes (S^2PD) using high-energy balls, widely known as the surface mechanical attrition treatment (SMAT), has been developed to induce in the workpiece routinely the desired nanocrystalline (nc) surface layer [14–31]. Similar to the SP method, the SMAT method also entails impacting repeatedly the workpiece multidirectionally under a controlled atmosphere, but using balls with sizes typically in the range 5–10 mm and impact velocities in the interval 5–15 m s^{-1} [25]. SMAT thus involves higher kinetics energies than SP, and is therefore expected to result in thicker nanocrystalline and work-hardened surface layers as well as deeper surface regions with larger residual compressive stresses. This expectation can be derived, for example, from a simple analysis based on the Hertz theory of the elastic contact between a sphere and a semi-infinite flat solid. Neglecting work hardening, strain rate sensitivity, friction and thermal effects, the depth of the plastic zone (h) can be calculated as follows [13]:

$$h = \frac{3\pi^{1/5}}{(1.145)^{1/4}(2/3)^{1/12}(2.5)^{1/20}} \frac{\rho^{1/5} v^{3/20} R^{2/3}}{E_H^{1/6} E_S^{1/30}} \quad (1)$$

where ρ, v and R are the density, velocity and radius of the impacting sphere, respectively, E_S is the elastic modulus of the solid and E_H is the equivalent modulus related to the Young's moduli and Poisson's ratios of the ball and solid materials. Eq. (1) predicts that the depth of the plastic zone, and therefore the thicknesses of the work-hardened layer and of the layer with residual compressive stresses, increases with the size, density and velocity of the impacting bodies, and therefore with their kinetic energy.

Recently, finite element modeling (FEM) has been used to provide the first quantitative comparison between SMAT and SP [25]. Assuming an Ni-base

* Corresponding author. E-mail: leon.shaw@uconn.edu

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C-2000 alloy as the workpiece and typical impact conditions for the SP (WC shots 0.3 mm in diameter, impact velocity 50 m s^{-1}) and SMAT (WC balls 7.9 mm in diameter, impact velocity 5 m s^{-1}) treatments, the FEM shows that with SMAT the deformation layer would be about six times thicker than with SP. Such a predication, however, does not take the cyclic strain hardening or softening of the material during SMAT into account, and thus only provides a general trend. Therefore, it would be highly desirable to have experimental evidence of the superiority of SMAT over SP, especially because Eq. (1) involves various simplifications and the FEM conclusions were obtained from single impact simulations. However, there have been no experimental studies in this direction. To address this deficiency, in this study we compared experimentally the effectiveness of SMAT and SP in inducing multiple changes in the workpiece microstructure and stress state simultaneously. To this end, we first subjected the same workpiece to SMAT and SP, then studied a multitude of microstructural features and stress states as a function of the depth measured from the processed surfaces. As will be shown below, the results obtained are consistent with the theoretical expectation and the FEM prediction, and demonstrate unambiguously that SMAT generates a thicker nanocrystalline surface layer, a deeper plastically deformed zone and a thicker surface region with larger residual compressive stresses than SP.

A well-annealed Ni-base C-2000 alloy with a low stacking-fault energy (1.22 mJ m^{-2}) [32] was chosen for the comparative study. The C-2000 alloy, which is a single-phase material with a face-centered-cubic (fcc) crystal structure and a nominal composition of 23Cr, 16Mo, 1.6Cu, 0.01C, 0.08Si and balance Ni (in wt.%), was received as plates of 3.2 mm thickness. In its annealed condition, it has an average grain size of ~50 μm, and contains microsized twins with few dislocations ($\rho = 3.6 \times 10^{11}$ m^{-2}) trapped between twin boundaries [27]. The SMAT was applied using a Spex 8000 high-energy mill equipped with a cylindrical hardened-steel container and five WC/Co balls 7.9 mm in diameter with an impacting velocity of ~5 m s^{-1}, and lasted for 30 min. The SP treatment was applied using a custom-made machine containing many steel shots of 0.5 mm in diameter with an impacting velocity of ~55 m s^{-1}, and lasted for 2 min to obtain a peening intensity with a coverage ratio of 350–400%. These SMAT and SP conditions were chosen because they have been shown to improve the fatigue resistance of the C-2000 alloy [33].

Figure 1 shows cross-sectional optical micrographs of the C-2000 alloy before and after SP and SMAT.

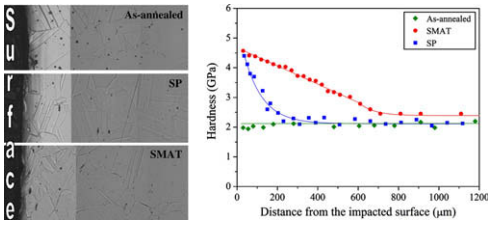

Figure 1. Cross-sectional optical micrographs of the C-2000 alloy before and after SP and SMAT, together with the profiles of Vickers microhardness.

Clearly, both SP and SMAT have induced plastic deformation in the workpiece near-surface, with the attendant work hardening. However, the surface plastic deformation is much more evident in the SMAT-processed sample, which has a four times thicker work-hardened zone (800 vs. 200 μm). These observations suggest that SMAT is a more effective surface treatment than SP. Nevertheless, a detailed study is needed to confirm this inference and to quantitatively compare SMAT and SP. In the present study, this comparative study was performed by the X-ray diffractometry (XRD) for various reasons. First, XRD can provide simultaneous quantification of the stress states and of a wide range of microstructural features in the processed workpiece, including crystallite sizes, deformation faults and twins, lattice parameters, elastic strains of the crystal lattice, macroscopic residual stresses and dislocation densities [27]. Second, XRD can be configured to explore a sample area of about 10 mm^2 (about 10^4 times the microstructural scale of the C-2000 alloy, which in its annealed condition has grains with an average size of ~50 μm), and thus the information obtained is statistically representative. Third, the collection of XRD patterns at different depths from the impacted surface is relatively simple, facilitating the quantification of depth-profile changes in the stress state and the wide range of microstructural features mentioned above.

Shown in Figure 2 are selected XRD patterns taken along the depth of the C-2000 alloy with SP and SMAT. They were measured by successive steps of material removal through electrochemical polishing followed by XRD data collection in a conventional diffractometer (Philips X'Pert MRD) operated at 45 kV and 40 mA using Cu K_α radiation ($\lambda = 1.54183$ Å) and the following collection conditions: 2θ in the range 30–80°, a step width of 0.02° and a count time of 5 s. The XRD pattern

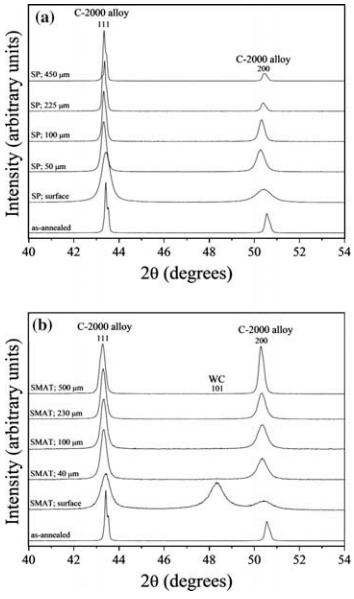

Figure 2. XRD patterns of the C-2000 alloy with SP (a) and SMAT (b), collected at selected distances from the impacted surface. The XRD pattern of the as-annealed C-2000 alloy is included for comparison. All XRD patterns have been normalized by imposing the same maximum intensity to facilitate the comparison.