Acta Materialia 97 (2015) 105–115

Contents lists available at ScienceDirect

Acta Materialia

journal homepage: www.elsevier.com/locate/actamat

Experimental assessment and simulation of surface nanocrystallization by severe shot peening

S.M. Hassani-Gangaraj [a,b,*], K.S. Cho [a,c], H.-J.L. Voigt [a], M. Guagliano [b], C.A. Schuh [a]

[a] Department of Materials Science and Engineering, Massachusetts Institute of Technology, Cambridge, MA 02139, USA
[b] Department of Mechanical Engineering, Politecnico di Milano, Milan 20156, Italy
[c] Center for Advanced Materials Technology (CAMT), Kookmin University, Seoul 136-702, Republic of Korea

ARTICLE INFO

Article history:
Received 11 March 2015
Revised 22 June 2015
Accepted 24 June 2015
Available online 12 July 2015

Keywords:
Surface nanocrystallization
Severe shot peening
Finite element
Dislocation density
Grain refinement

ABSTRACT

Surface nanocrystallization is an effective approach to bypass the difficulties of synthesizing bulk nanocrystalline material and yet exploit its unique advantages in service. This study uses air blast shot peening over a wide range of coverage (peening time), from conventional to severe, to generate nanostructured surface layers on high strength low alloy steel. Electron microscopy observations were carried out to systematically study the degree and the mechanism of grain refinement as the severity of deformation increases. A model linking finite element simulation of severe shot peening to dislocation density evolution due to the accumulated plastic strain was developed to predict the resultant grain/cell size gradient in the surface layers. The proposed framework establishes a physical connection from processing parameters such as media size, velocity and peening coverage to the resultant structure, opening the possibility of designing a severe surface peening process to achieve a desired nanostructure.

1. Introduction

Most material failures, including fatigue fracture, fretting fatigue, wear and corrosion are very sensitive to the structure and properties of a material's surface, and many of these properties are known to improve in fine grained and nanocrystalline (NC) materials [1,2]. As a result, methods to achieve a nanocrystalline surface layer over bulk material are of broad interest, especially since surface nanocrystallization [3] processing techniques may bypass difficulties of synthesizing bulk NC components and yet exploit the advantages of NC materials in service. Mechanically induced surface nanocrystallization is generally effected through repeated multidirectional plastic deformation caused by high velocity impacts. Such impacts create high dislocation densities through strain localization in shear bands, followed by recombination, rearrangement and annihilation of some dislocations upon subsequent impact events. The initial grains are thereby subdivided into a large number of sub-grains (or domains) separated by small angle grain boundaries [3,4], which can also gradually accumulate misorientation to become high-angle boundaries. Equiaxed ultrafine or nano grains with random crystallographic orientation have been found by TEM observation in a variety of studies of this kind [4–6].

A variety of shot peening derived processes have been developed, although they all fundamentally exploit the same materials mechanics and structural evolution mechanisms to achieve surface nanocrystallization. For example, ultrasonic shot peening (USSP), sometimes called surface mechanical attrition (SMAT) [4–13] uses a dynamic generator at frequencies ranging from 50 Hz to 20 kHz, to resonate peening media against a sample surface. Air blast shot peening employs compressed air to accelerate shots, and is widely used industrially because of its simplicity, low cost and applicability to variety of targets. Air blast shot peening becomes a severe process that accesses ultrafine and NC structures when certain combinations of peening parameters are used to multiply the kinetic energy of the shot impacts [14–18]. In general, we differentiate severe shot peening [19–21] from conventional shot peening in order to emphasize its aim at generating ultra-fine grained or NC surface layers.

Surface nanocrystallization mechanisms can be related to the magnitude of the stacking fault energy [22]. In materials with larger stacking fault energy such as iron, TEM observations after SMAT revealed that dense dislocation walls and tangles are generated inside the original grains. Upon further straining, the dislocation walls and tangles transform into sub-boundaries with small misorientation via annihilation and rearrangement in order to minimize the total energy of the system. Eventually, sub-grain

* Corresponding author at: Department of Materials Science and Engineering, Massachusetts Institute of Technology, Cambridge, MA 02139, USA.
E-mail address: mhassani@mit.edu (S.M. Hassani-Gangaraj).

http://dx.doi.org/10.1016/j.actamat.2015.06.054
1359-6454/

boundaries evolve into high-angle grain boundaries that subdivide the original grains into refined structures [23]. In low stacking fault energy materials such as austenitic stainless steel, the prominent features include planar dislocation arrays and mechanical micro-twins at higher strains [6,10]. The original coarse grains thus become sub-divided by lamellar twins with nanometer-sized thickness. Upon further straining dislocations inside the lamella arrange themselves into dislocation walls traversing the thickness of the microtwin lamellae. Twin–twin intersection also leads to nanometer sized blocks. In the case of SMATed copper (medium stacking fault energy) intermediate behavior with two different mechanisms of refinement is observed [12]. In the subsurface layer, dislocation activity leads to dislocation cells instead of tangles, but at the top surface layer (within 25 μm), the twinning-related refinement mechanisms seen in low stacking fault energy materials are operative.

Modeling of nanocrystallization mechanisms during severe shot peening has not been extensively treated. In Ref. [24] a finite element analysis of the mechanics of peening was presented. However, no connection was given to the microstructural evolution process, grain size and the gradient of nanostructure that naturally evolves during peening. A physical model of structure evolution would be useful to engineer the surface layers and design a peening process to attain a desired nanostructure.

It is the purpose of this paper to present a systematic study of surface nanocrystallization by severe shot peening. Using air blast peening, a wide range of coverage was adopted to span both conventional and severe shot peening regimes. A hybrid numerical model was developed with the aim of assessing microstructural evolution during shot peening. Scanning electron microscopy (SEM) and transmission electron microscopy (TEM) observations were conducted to study the grain refinement, surface nanocrystallization and also for comparison with a finite element simulation incorporating dislocation density evolution. The comparison of dislocation cell size obtained by numerical framework and those measured by TEM/SEM observation shows a satisfactory and promising agreement.

2. Material and experiments

The substrate material considered in this study is high strength low alloy steel ESKYLOS6959 (equivalent to DIN 35NiCrMoV12-5 or AISI 4340). Its chemical composition is summarized in Table 1. AISI 4340 is one of the most widely studied materials after shot peening. The reason is that its application is mainly power transmission gears, shafts and aircraft landing gears where fatigue is always the first design consideration, and shot peening has been widely applied to these components to improve fatigue behavior.

Cylindrical specimens of 7.52 mm diameter in the target section were machined from a forged bar. All specimens were extracted from the bar in the same radial position to ensure similarity of microstructure. The bar had been quenched from 880 °C in water and then tempered at 635 °C for 5 h.

Standard cast steel shots, S230, were accelerated in an air blast machine to conduct shot peening. Shot peening was performed with 100%, 200%, 650%, 1000% and 1300% coverage to examine the evolution of microstructure as coverage increases. 100% and sometimes 200% are the typical coverage levels used in conventional shot peening to generate an appropriate field of compressive residual stress and sufficient work hardening. The higher levels of 650%, 1000% and 1300% represent the severe shot peening regime, in which significant grain refinement and eventually surface nanocrystallization are produced. Shot peening coverage can be effectively related to the peening time. For instance, for a given target area and set of peening parameters, the time needed to attain a coverage of 1000% is ten times the time needed to attain the full coverage (100%). The angle between the shot flow and the target surface in the experiment was set equal to 90° for simplicity, and because this is a recommended angle for uniform residual stress generation. Randomly deviating from perpendicular impacts might also be beneficial in terms of inducing very localized multidirectional severe plastic deformation. The shot peening intensity as measured on "Almen A" strip was 18, which is an index of the total energy of the treatment. Using the approach of Ref. [25], we may connect the Almen intensity to the shot flow velocity for a fixed shot; in this manner the effect of shot velocity on nanocrystallization can be inferred for practical applications.

Table 1
Chemical composition of the present high strength low alloy steel (wt%).

C	Mn	Si	Cr	Mo	Ni	V	Fe
0.3–0.4	0.4–0.9	0.15–0.55	1–2	0.35–0.9	2.5–4.5	0.05–0.25	Balance

The microstructure of peened samples was characterized using a JEOL 2010F analytical microscope operated at 200 kV and FEI/Philips XL30 FEG ESEM at 20 kV. The peened samples were mechanically cross sectioned, polished and mounted on copper grids for TEM observation. To prepare TEM specimens, two cylindrical disks were prepared first by cutting the shot-peened specimens. These disks were glued face-to-face on a metal plate, and then mechanically polished to make thin foils. This procedure was needed to preserve a disk edge that included the severely deformed layer (top surface), as well as observe the non-deformed layers simultaneously. The two polished parts of the disk were then re-glued onto a slot grid, and were ion-milled using a Gatan PIPS instrument with an ion accelerating voltage of 5 kV at 5°. The distance of a given observed region from the free surface was measured in the TEM using low-magnification imaging. The mean grain size was evaluated from layers within a vertical range of 5 μm. SEM observations were also conducted to evaluate grain refinement. 8% Nital was used as etchant to reveal the final microstructure (i.e., lower bainite and/or tempered martensite) with the cell boundaries. All the SEM observations were conducted under the same magnification factor of 2000X to attain better statistics. The cell (and/or grain) sizes reported are area-equivalent circular diameter for structures that are dominated by equiaxed cells, and length for the structures dominated by lamellar cells [26]. The total counts for each size measurement was at least above 70. For the low coverage levels (100% and 200%), it was difficult to use TEM because of the relatively coarse grains and the correspondingly limited view of the relevant structural scales, which are coarser than the TEM observations. Similarly, for high coverage levels (650%, 1000% and 1300%), the refined grains were too small to evaluate by SEM.

3. Numerical framework

3.1. Finite element simulation

Finite element models of a single impact and multiple impacts are developed and linked to a dislocation density evolution model. The single impact model, as the unit process of peening, was used to examine the effect of media size, velocity and hardness on the induced refinement. Multiple impacts model was used to realistically simulate the induced refinement by peening with different coverage levels, from 100% to 1300%.

Two dimensional axisymmetric models of a target impinged upon by a single impact were developed with the commercial finite element code Abaqus Explicit 6.10-1 [27]. The dimension of the target was chosen to be $5R \times 5R$, where R is the shot radius,