NANOSTRUCTURING THE SURFACE LAYERS IN METALLIC MATERIALS BY MEANS OF ULTRASONIC IMPACT TREATMENT

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In recent years, great progress has been made on the study of ultrafine–grained (UFG) and nanocrystalline (NC) materials having an average grain size smaller than 1 μm, with reasonably homogeneous and equiaxed microstructures, and with a large fraction of high–angle boundaries [1]. The most effective methods of severe plastic deformation (SPD) used widely to produce bulk UFG metals and alloys, such as equal channel angle extrusion (pressing), high pressure torsion or accumulative roll bonding, operate at low strain rates applied at ambient temperatures [2].

Fabrication of surface layers comprising UFG or NC grain structures also has drawn increasing attention due to the fact that these layers can support the overall superior functional properties for metallic components. The vast majority of methods for superficial nanocrystallization uses high velocity projectiles, which provide impact deformation of surface layer with strain rates as high as approx. 10^3–10^4. The ultrasonic impact peening/treatment (UIP/UIT) described here demonstrates good efficiency with regard to the strain induced grain refinement in different metallic materials [3, 4]. It is among the most effective methods used for surface severe plastic deformation (S^2PD).

The basic concept and equipment for the UIP processing are partially described in a number of recent publications [3, 4]. The energy required for this technique is supplied by an ultrasonic generator at a frequency of 18–22 kHz and a power output of 0.3–4.0 kW. The generator is connected to an ultrasonic instrument, which consists of a piezoceramic or magnetostrictive transducer, an ultrasonic horn and a special impact head positioned on the horn tip. Impact loading is caused by the vibration of an ultrasonic horn; the specimen is exposed to repetitive impacts by the pin/pins positioned between it and the plane tip of the horn. The average induced frequency f_i of impacts in this loading scheme is 1–3 kHz. Both the total mechanical energy applied to the material and the total plastic strain are gradually accumulated with the processing time.

A number of fundamental parameters that determine the UIT regime – both experimentally obtained and calculated – need to be analysed. They include the UIT impact energy defined as $E_{US} = 2\pi^2 f_{us}^2 \xi^2 m_p$, where f_{us} and ξ are the frequency and amplitude of the ultrasonic horn vibrations, respectively; the indent diameter *d*; the peak power density defined as $I_0 = E_M/(S\tau)$, where $S = \pi d^2/4$ is the spot area; the duration τ of a single impact is 35 μs; the mechanical energy E_M applied to the material surface during a single impact of UIT, which is sufficiently low (~2 mJ); the shock pressure P_{SW}; the repetition rate (frequency of ultrasonically induced impacts f_i); the total mechanical power accumulated during the UIT process, defined as $\hat{I}_{US} = I_0 f_i t$, where *t* is the processing time; the effective strain $\bar{e}$ assessed on the basis of the changes in the specimen dimensions; shear γ and true e strain extent, deformation work done A, increase in the local surface temperature Δ*T*, and so on. The total mechanical power $\hat{I}_{US}$ applied to a material during the UIT process can be a suitable parameter to compare the UIT–induced changes with those observed after other modification processes.

Different schemes and fundamental parameters of ultrasonic impact treatment (UIT) are analyzed. Structural formation is studied in metallic materials subjected to severe plastic deformation caused by high–frequency impact loading during UIT. The determinative effects of several UIT parameters on the nanostructurization of metallic surface layers are shown as follows: high strain extent and high strain rate, successive multidirectional impact loads containing the shear component of load (sliding impacts), and deformation induced temperature rise sufficient to initiate the dynamic recovery/ recrystallization or phase transformations.

The stress, strain and strain rate involved in the UIT process can be estimated by applying either Hill's deformation model or finite element analysis. Generally, the strain rate is as high as about 10^3–10^4. It depends on the striker velocity (peak power density), which is determined by the amplitude of the ultrasonic horn vibrations. Naturally, the largest strain occurs in the topmost surface layer of the treated specimen. Additionally, the true strain can be evaluated by the detailed OM/SEM studies of the cross–section of the treated specimen, which allow analyzing the position of grain boundaries with respect to the treated surface. The magnitude of true strain for the UIT–treated Fe specimens was shown to be e = 4.5 (assuming the correlation of shear strain and the tilt angle α of the grain boundaries and the treated surface as $e = \gamma/\sqrt{3} = (\tan \alpha)/\sqrt{3}$).

Deformation heating, which is known to be an important parameter in structural evolution and hardening process in the surface layer, can affect both the structural and phase transformations and the material ductility. Owing to possible initiation of dynamic recovery or recrystallization the temperature increase is an important constituent in the mechanism of nanostructurization. Assuming adiabatic heating, it is possible to estimate the temperature rise within the topmost surface layer accounting for the deformation work done (integrating the product of stress and strain in the surface layer) and the density and the specific heat capacity of the specimen material.

An important feature of the UIT–processed materials is that the imposed strain varies across the treated surface layers, and the strain being maximal at the top surface is rapidly reduced to zero beneath a certain depth (~30–150 μm dependently on the strength of the material). After UIT, significantly increased microhardness and compressive residual stresses are usually observed in the layer of about 0.25–1 mm thick.

The peculiarities of the structural mechanisms for plastic deformation and formation of ultrafine grained (UFG) or nanocrystalline (NC) grain structures in the surface layers of metallic materials depend on the mobility of dislocations and operation of slip/twining systems and/or strain/stress induced phase transformations [4]. The type and number of operative deformation mechanisms depend on the type of crystalline lattice of the main phase. The structural formation in face center cubic (FCC) metals subjected to S^2PD induced by the UIT process depends on stacking fault energy (SFE) magnitude of the material, which predetermines the width of dislocation splitting in slip planes and, in its turn, cardinally changes both the mobility of dislocations and the mechanism of structural evolution. Many sliding systems of dislocations significantly affect the structural evolution in base center cubic (BCC) metals during the deformation process. Owing to the high mobility of dislocations and their ability to cross slip to overcome the obstacles, the formation of a dislocation cell structure at strain extent of ~0.4–0.5 is most reliable. It is the main feature of similitude between the BCC metals and high SFE FCC materials (aluminum). In hexagonal close packed materials, the materials with limited slip systems as titanium or zirconium alloys, to accommodate the deformation stresses, twining and/or phase transformations are involved in addition to the dislocation activity in the straining process. Multi–system twining occurring from the very beginning of straining is characteristic to HCP Ti and Zr. The structural mechanisms of grains subdivision in HCP titanium and in two Zr based alloys, which comprise different volume fractions of second β–phase (BCC), are analyzed.

Fig.1 shows examples of the nanostructures formed in surface layers of AISI 326 stainless steel (a, b), alpha titanium and AMg6 aluminum (c,d) alloy after S^2PD induced by the UIT process.

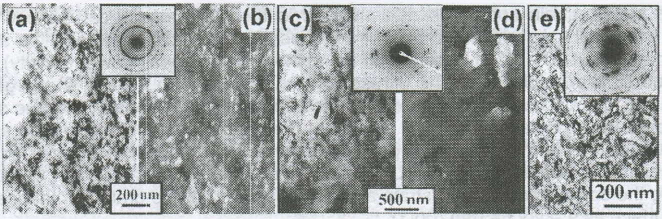

Figure 1 – Nanostructures formed in surface layers of AISI 326 stainless steel (a,b), AMg6 aluminum (c,d) and VT1–0 alpha titanium alloy (e)

It is shown that, at the UIT process, structural mechanisms of plastic deformation and nanostucturization in the surface layers of metals and alloys with different crystalline lattices exhibit certain peculiarities. It is established that the materials that posses many slip systems (e.g., BCC iron) or high values of stacking fault energy (SFE) (FCC aluminum) deform via the dislocation mechanisms, and a specific structure evolves through the following sequential changes in the dislocation structure: increase in dislocation density; formation of dislocation bundles, tangles and their rearrangement into subboundaries; increase in misorientation of neighboring subgrains due to annihilation of dislocations of different polarities; and transformation of subgrains to new grains with thin boundaries at dynamic recovery/recrystallization occurring due to local deformation heating. On the contrary, materials with limited slip systems (HCP titanium alloys) or low SFE (austenitic stainless steels), additional mechanisms such as twining and/or phase transformations are involved to accommodate deformation stresses. Twining can occur from the very beginning of straining (Ti, Zr) or can be activated after the critical strain extent (austenitic stainless steels).

The UFG/NC microstructure formed in the topmost surface layers during the UIT process, the high level of internal compressive stresses in the hardened surface layers, and diminished surface roughness, play key roles in the formation of a complex of improved physical and mechanical properties of metallic materials. Thus, UIT can be considered as the basis for the development of new technologies capable of producing modern construction and functional materials with enhanced fatigue durability, and improved wear and corrosion resistance, from the raw materials with different strength, phase composition, and structures.

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