# Generation of nanostructure by SMAT (Surface Mechanical Attrition Treatment): basic concept, different processes and applications

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**ABSTRACT**

In the case of structural materials, surface engineering can lead indirectly to the innovation of genuinely new materials based on conventional materials. This paper will summarize the recent work related to a kind of new nanomaterials produced by the SMAT (surface mechanical attrition treatment). The results concerning the basic concept, the different processes, the properties of the materials and the potential applications will be presented.

## SUBJECT INDEX

SMAT, Nanostructure, tensile properties, nanonindentation

## INTRODUCTION

Nanocrystalline materials are characterized by ultrafine crystalline grains in the nanometer range, separated by grain boundaries or interfaces. They possess fundamentally different physical and chemical properties and behavior from their traditional coarse-grained polycrystalline counterparts and find potentially important technological applications. In terms of the grain refinement mechanism induced by plastic deformation, a novel surface mechanical attrition (SMA) technique was developed for synthesizing a nanostructured surface layer on metallic materials in order to upgrade the overall properties and performance. The concept of surface nanocrystallization (SNC) of crystalline materials was first presented by Lu and Lu [1]. This kind of surface modification greatly enhances the surface properties without changing the chemical composition. It is also a flexible approach that makes it possible to obtain specific structural/property requirements localized on the surface of the material. Surface nanocrystallization is much easier to carry out and more economical than bulk nanocrystallization. It has a high future potential. The different process of SMA technique and the nanostructure of the SMA-treated surface layer will be described. The grain refinement mechanism of the surface layer during the SMA treatment will be analyzed in terms of the nanostructure observations in several typical materials (Fe, Cu, Stainless steels, Ti, etc.). The nanostructured layer with a grain size of 10 to 15 nm was generated on the surface of material up to a depth of 50µm. Significant enhancements in mechanical properties of the nanostructured surface layer in different materials will be analyzed. The evidence obtained so far has already indicated that a nanostructured surface layer synthesized by means of SMAT on metallic materials provides many unique opportunities in terms of both basic scientific research and technological applications. Very high yield stress (5 times of the base material) on the surface layer of the material obtained by the SMAT has been observed in stainless steel 316L. The effect of surface nanostructures on the mechanical behavior and on the failure mechanism of metallic material shows the possibility to develop a new strength gradient composite.

## BASIC CONCEPT OF SMAT

Lu and Lu [1] classified the surface nanocrystallization of materials into three categories according to the basic concept of nanocrystalline materials and their formation mechanism: (1) nanocrystallization by surface coating (or deposition); (2) surface self-nanocrystallization; and (3) hybrid surface nanocrystallization.The first type of surface nanocrystallization (illustrated in Figure 1a) is based on various coating and deposition technologies such as PVD, CVD and plasma processing. The coated materials can be either nanometer-sized isolated particles or polycrystalline powders with nano-sized grains. The coated layer and the substrate can be different or made of the same type of material. The most important factors in the process are bonding of the coated layer with the substrate and bonding between particles while maintaining the nanostructure. The basic idea behind the second type of surface nanocrystallization is to transform the surface layer of the materials into the nanocrystalline state while keeping the overall composition and/or phases unchanged. This type of surface self-nanocrystallization (shown in Figure 1b) can be produced by means of mechanical or thermal activation. Mechanically induced surface self-nanocrystallization (MISS-NC) involves a grain refinement process through the application of mechanical treatments. Thermally-induced surface self-nanocrystallization (TISS-NC) can be produced by means of a phase transformation such as melting or solidification. By controlling the melting and solidification kinetics of the surface layer, a nanocrystalline structure can be formed. This kind of transformation has been observed experimentally in a variety of metallic materials using laser beam or e-beam glazing. The third type of process (shown in Figure 1c) is carried out in two steps. The first step is to produce a nanostructured transformable layer and the second is to combine it with a chemical, thermal or metallurgical process to produce a nanocrystalline layer with different chemical compositions or different phases. It is also possible to develop a process to produce SNC by simultaneously combining these two steps.

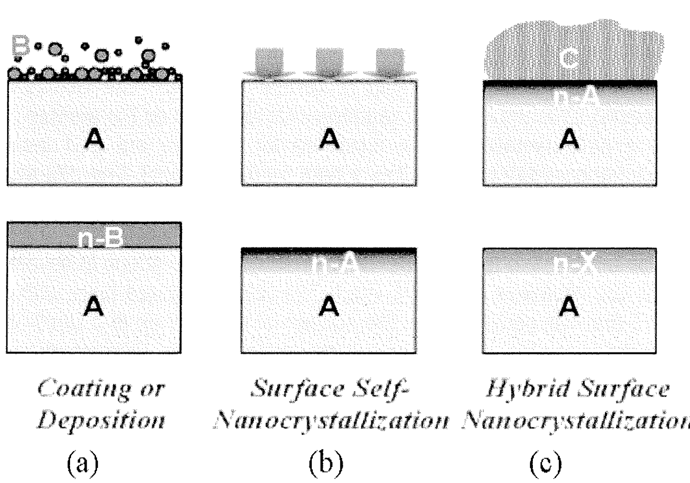



Figure 1 Schematic illustration of three types of surface nanocrystallization processes: (a) surface coating or deposition; (b) surface self-nanocrystallization; (c) hybrid surface nanocrystallization.

## PROCESS FOR PRODUCING SURFACE NANOCRYSTALLIZATION

Various possible processes have been analyzed and discussed by Lu and Lu [1] concerning the mechanism underlying 2$^{nd}$ and 3$^{rd}$ type surface nanocrystallization i.e. grain refinement induced by plastic deformation. A new series of patented techniques has since been developed, namely **surface mechanical attrition (SMA)**, to synthesize a nanostructured surface layer on bulk metallic materials. As a result of plastic deformation of the surface layer induced by mechanical attrition, the coarse-grained structure in the surface layer is refined to the nanometer scale without changing the chemical composition. The SMA technique has been successfully applied to various kinds of materials including pure metals [2,3,4], steels [5,6], Al alloys[7], on which a nanostructured surface layer up to 50 μm thick has been obtained. A significant enhancement of the overall properties and performance of the materials has been observed after SMA treatment. During the last six years, different types of equipment have been developed, based on the concept proposed, to produce 2$^{nd}$ type surface nanocrystallization. Three categories of surface mechanical attrition (SMA) machines have been developed. The key issue with all these techniques is the possibility of introducing random severe plasticization on the surface of bulk materials.

The first technique is based on the vibration of spherical shot using high power ultrasound. The shot are placed in a reflecting chamber (including an ultrasonic concentrator) which is vibrated by an ultrasonic generator, after which the shot are resonated. Because of the high frequency of the system (20kHz), the entire surface of the component to be treated is peened with a very high number of impacts over a short period of time. Figure 2 gives a diagram of a typical device used to treat samples and a photograph of one example of such kind of machine which produce different moving surface amplitudes. The main process parameters are the treatment time, the shot diameter, the number of shots and the temperature. The diameter of the shot typically used for this type of process is 0.4 to 8mm, which is greater than the ones used for conventional shot peening treatment.

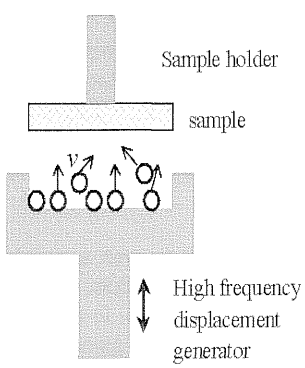
The second type of machine is based on the mechanical vibration of a reflecting chamber with shot ranging in diameter from several mm to 10mm. The frequency is lower than that of an ultrasonic system, but the shot used can be much larger than those used in the previous system. It is also easier to introduce multidirectional movement of the reflecting chamber. Figure 3 gives a photo of one possible configuration for this type of machine. Several new generation machines are currently being developed.

The third type of machine is based on a pneumatic-assisted shot jet with a nozzle system. The key to its success is the use of spherical shot and a random shot jet device. In classical shot peening, the shot jet is practically unidirectional. In the new system, different possibilities of relative movement between the target sample and the shot jet have been explored. Figure 4 shows the main working principle for this type of machine.

The above three types of machines are all based on the following concept. The system must introduce a large number of defects and/or interfaces into the surface layer so that its microstructure will be transformed into nano-sized crystallites. In other words, a grain refinement process on the nano-scale is needed in the surface layer while the structure of the coarse-grained matrix remains unchanged. During treatment, the surface of the sample is impacted with a large number of flying shot over a short period of time. Each impact induces plastic deformation with a high strain rate in the surface layer of the sample, as shown schematically in Fig. 6. Consequently, repeated multidirectional impacts at a high strain rate on the surface of the sample result in severe plastic deformation and grain refinement progressively down to nanometer regime for the entire surface of the sample. The velocity in the mechanical vibration system is difficult to evaluate. In the ultrasonic system, the velocity of the shot is about 5m/s to 20m/s. Its relationship with the vibration frequency has not been systematically studied. However the results were excellent for all the frequencies used. The initial results obtained for the real temperature of the surface of the sample during treatment show a higher temperature in the case of ultrasonic-assisted surface mechanical attrition (UASMA) treatment and mechanical vibration assisted SMA (MVASMA) when compared with classical shot peening treatment.

The major differences between classical shot peening and the new SMA process are as follows:

(1) the shots used in classical shot peening are smaller (about 200 µm to 1mm) than they are for the SMA process (300µm to 10 mm);
(2) the shot shape requirements are not the same; because of the high strain deformation and the high strain level required to produce a nanostructure using SMA, perfectly spherical shot must be used to reduce the risk of wear and the damage in the surface layer;
(3) finally, in order to reduce the grain size to nanoscale level, a random directional treatment is necessary compared with classical shot peening which is a directional treatment (the angle between the shot jet and the sample surface is quite close to 90° in many cases).



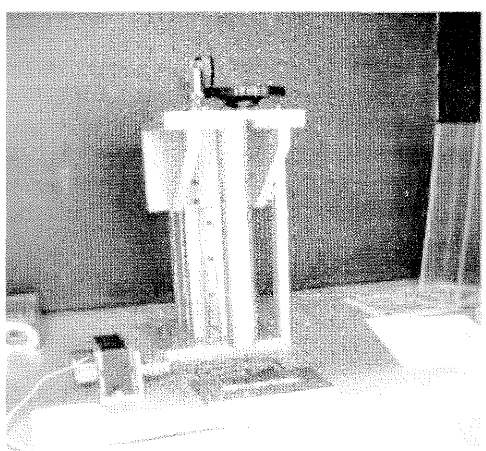



Figure 2 Schematic illustration of the ultrasonic-assisted surface mechanical attrition treatment set-up.

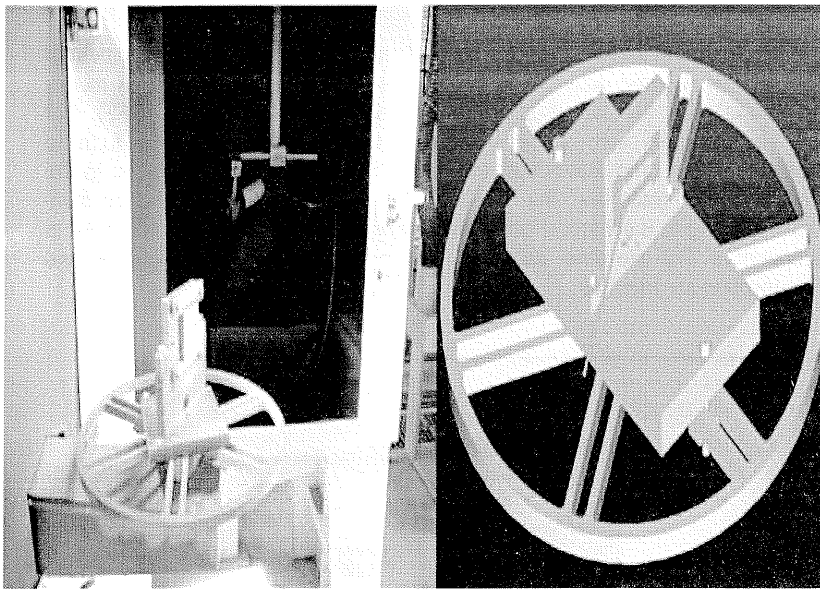


Figure 4 Schematic illustration of the pneumatic-assisted shot jet surface mechanical attrition treatment set-up and repeated multidirectional plastic deformation in the surface layer of the sample induced by impact of the peened shot.

## SURFACE NANOCRYSTALLIZATION MECHANISM

Understanding how nanocrystallites are formed during the SMA process is crucial for the development of the SMA technique. Owing to the gradient variation of the strain and the strain rate from the treated top surface (both are high) to the deep matrix (essentially zero, as schematically shown in Fig. 5), a gradient grain size distribution from a few nanometers (in the top surface layer) to several microns develops in the SMA treated sample providing a unique opportunity for examining the microstructural characteristics at different strain levels and strain rates. This enables the underlying mechanism of deformation-induced grain refinement in the micron~nanometer regime to be revealed.

Like the grain refinement mechanism during plastic deformation of bulk metals, the formation of nanostructures from coarse-grained polycrystals in the surface layer during SMA treatment involves various dislocation activities and the development of grain boundaries. Plastic deformation behavior and dislocation activities in metals depend strongly on the lattice structure and stacking fault energy (SFE). For example, in materials with a high SFE, dislocation walls and cells form to accommodate strain, and sub-boundaries form to subdivide coarse grains. In the case of low SFE materials, the plastic deformation mode may change from dislocation slipping to mechanical twins (especially under a high strain rate and/or at low temperature. For the other cases, a mixture mechanisms of dislocations and twins intersection are reported.

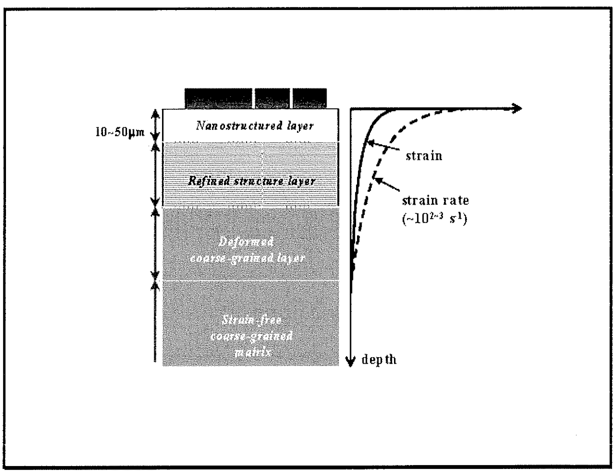



Figure 5 Schematic illustration of the microstructural characteristics and strain and strain rate distributions inside the surface layer subjected to SMA treatment.

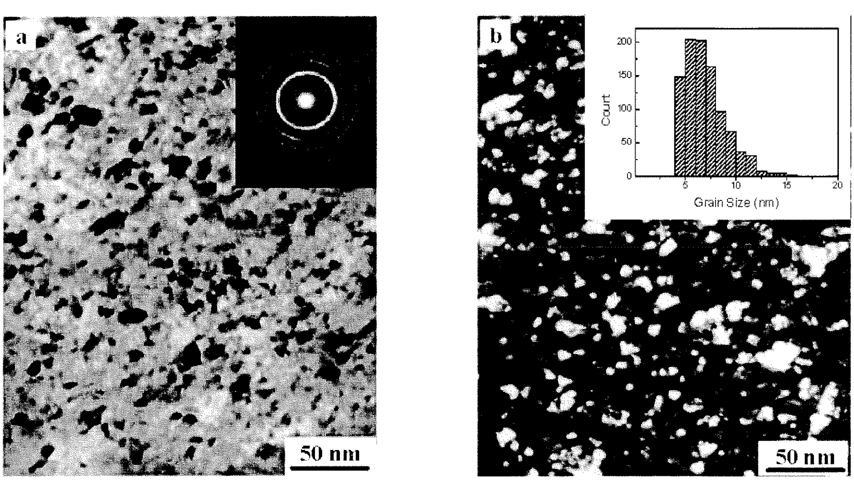



Figure 6 (a) Bright-field and (b) dark-field TEM images showing planar microstructure of the top surface layer in the SMA-treated Fe sample (the insert is a statistic distribution of the grain size derived from the dark field TEM images).

## MECHANICAL BEHAVIOR AND RESIDUAL STRESS

In order to study the effect of SMA on the mechanical behavior of the material, a tensile test was carried out with a 1mm thick 316L stainless steel sample with a ultrasonic SMAT during 15 minutes. The top layer was a surface nanocrystalline layer about 10 micrometers thick, depending on the treatment parameters (time, energy, temperature etc.). Underneath it is a refined structure layer in which the grain size gradually changed from nanometer scale to normal sizes in the base material. The material properties in this layer varied with the depth. The region near the top surface was subjected to severe plastic deformation while the region near the base material mainly underwent elastic deformation. The experimental results are shown in Fig. 7. The curve for the treated material is obviously higher than that of the untreated material. It shows that all the strength-related parameters of the treated material increased after SMAT. The yield stress of the untreated and treated samples is $\sigma_s^b = 280\text{MPa}$ and $\sigma'_s = 550\text{MPa}$ respectively. The SMAT resulted in a 96% rise in the yield stress. The ultimate stress for the untreated and the treated materials is $\sigma_m = 620\text{MPa}$ and $\sigma'_m = 700\text{MPa}$ respectively i.e. an increase of 13%. The moiré interferometry technique was used [8] to measure the in-depth residual stress distribution in a SMAT 316L stainless steel. Two residual stress release methods were used, namely cutting and incremental hole-drilling. The experimental results of the two methods were compared. The effect of the residual stress fields was evaluated. After one analyse using the finite element, we have observed that the global distribution of residual stress can not contribute to the improvement of yield stress. The recent results shown that the main contribution can be the very high tensile behavior of the surface layer. The figure 8 shows that the mechanical behavior top surface layer obtained by the thin film tensile test [9].

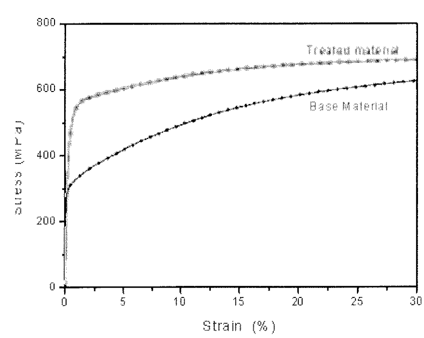



Figure 7 Comparison of the stress Strain relationship of treated and Untreated samples

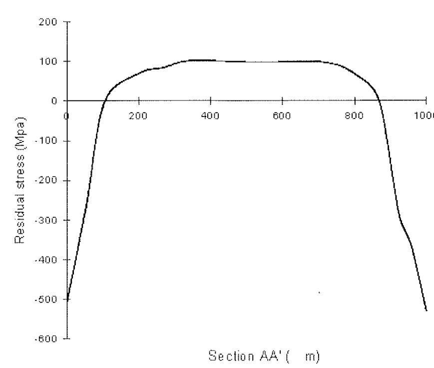



Figure 8 The through thickness residual stress distribution using the moiré interferometry technique

## CONCLUSION

The evidence obtained so far has already indicated that a nanostructured surface layer synthesized by means of SMA treatment on metallic materials provides many unique opportunities in terms of both basic scientific research and technological applications. Other advantages of this technique include the fact that many existing processes can be used to obtain a nanostructured surface layer with a high level of productivity. The surface nanocrystallization of metallic materials will certainly provide a complementary process to the nanocrystallization of bulk materials. With increasing investigations on the processing and properties of the nanostructured surface layer, industrial applications of this new technique to upgrade traditional engineering materials and technologies in the near future can be anticipated. In the future, advanced techniques such as SThM (Scanning Thermal Microscopy) and the nanoindentation will be used for the rapid identification of nanostructure and the local mechanical behavior study [10]-[13].

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