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Mechanics of High Strength and High Ductility Materials

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Abstract

The ability to create structural materials of high yield strength and yet high ductility has been a dream for materials scientists for a long time. This paper will summarize the recent work related to the study of the mechanical behavior of the surface nanostructured materials using SMAT (Surface Mechanical Attrition Treatment). Significant enhancements in mechanical properties of the nanostructured surface layer in different materials will be analyzed. 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. The nanoindentation method is developed for the investigation of the gradient structures. The role of the residual stress is studied. The results shown that the compressive residual stress is one of the key mechanisms for the enhancement and the extraordinary properties of layered nanostructured metallic stainless steel sheet. Finally, some new results of the simulations will be presented and discussed. The simulation of SMAT process using the finite element methods will be compared with the experimental investigation using high speed camera. The computational models successfully simulate the enhanced ductility and strength and provide valuable information about the mechanical behavior of nanostructured layered composite material.

Keywords: Nanostructured materials; finite element modelling (FEM); Surface Mechanical Attrition Treatment (SMAT);mechanical properties.

1. Introduction

Nanostructured (NS) materials have attracted significant research interests in the past decades owing to their superior yield strength over their coarse grained counterparts [1]. However, NS materials always suffer from the low ductility which hindered their development beyond laboratory-scale. Producing structural NS materials with not only high yield strength but also the high ductility therefore becomes the ultimate goal for materials scientists.

Surface Mechanical Attrition Treatment (SMAT) [2] was one of the recently developed fabricating methods to produce materials composed of nano-grained surface layer, refined grained subsurface layers and nano-twinned structure which render the high strength as well as high ductility, by actuating a number of spherical projectiles to strike the sample surface [2, 3]. Fig. 1 schematically illustrates the experimental setup of SMAT. This technology has been employed by material scientists for a number of materials, such as pure iron [4], pure titanium [5], pure copper [6], pure cobalt [7], pure nickel [8], aluminum alloy [9] and stainless steel [10], for producing nano-grained

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materials. The early studies showed that the yield stress of the SMATed metals has significant enhancement while the ductility drops drastically when compared to their pristine forms. In order to improve the ductility, NS layered composite materials adopting SMAT and warm co-rolling techniques was developed [11]. Recently, as more extensive researches have been conducted on the parametric studies of the SMAT process, the optimized conditions have been obtained to produce NS metals with rich nano-twins which possess both high strength and high ductility. The missing pieces of the knowledge on the mechanisms and roles of some of the key factors, like failure mechanism, strain-rate and residual stress related to the SMAT process on the mechanical properties of the treated materials have also been revealed [11, 12]. Most recently, the experimental based results have been further analyzed to build the computational models and hence, the strength and ductility of the novel materials related to different parameters of the SMAT process can be approximately estimated.

In this review paper, the recent works related to the study of the mechanical behavior of the surface NS materials using SMAT are summarized. The focus is directed to the treatment of a single sheet of 1 mm thick AISI304 stainless steel (304SS) and three-layered co-rolled SMATed 304SS which have both high strength and high ductility, as shown in the engineering stress- strain curves of Figs. 2(a) and 2(b), respectively. The recent experiments carried out to study the mechanical properties of the SMATed materials and optimum parameters of the SMAT process are presented. The roles of the NS surface layer and residual stress on the enhancement of ductility and strength are addressed with the latest computational models introduced.

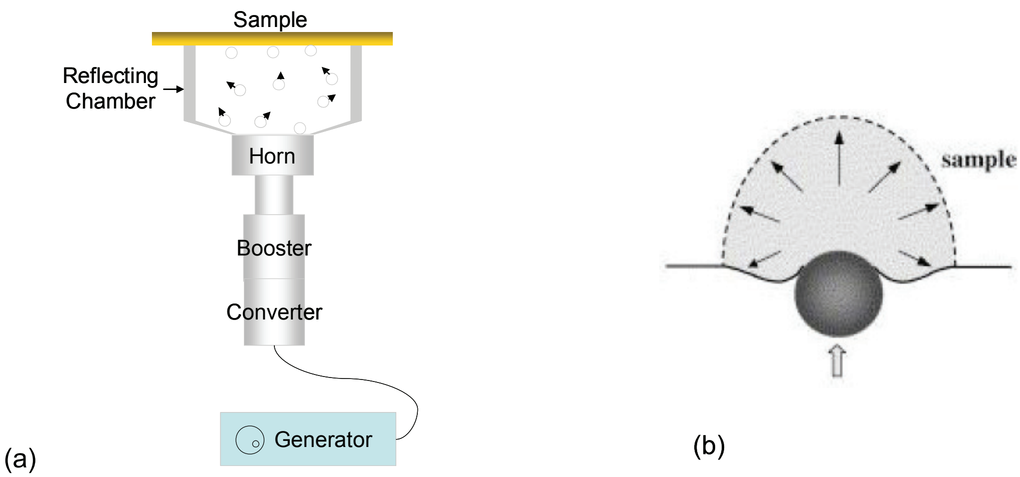
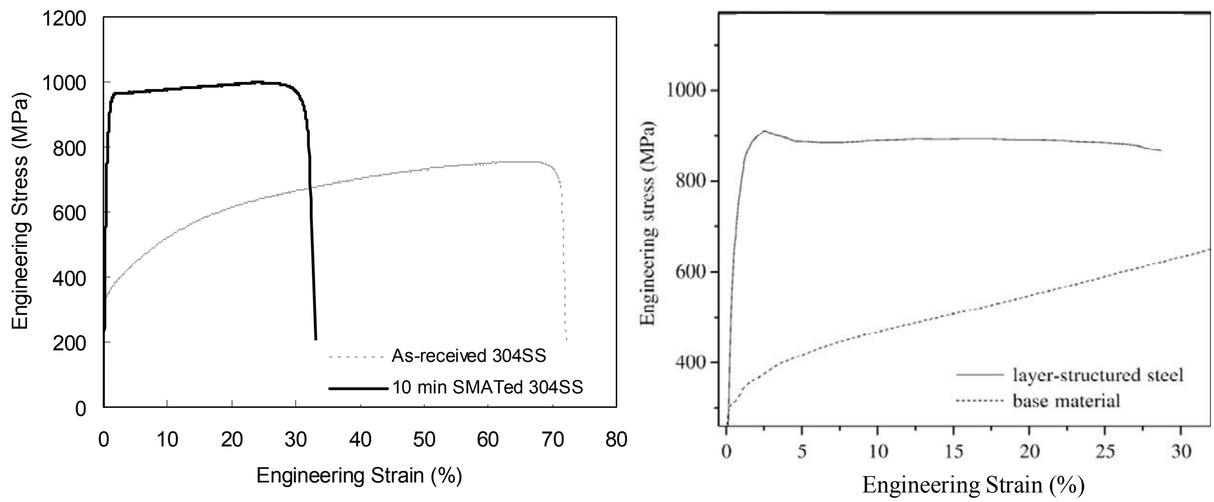


Fig. 1. Experimental setup of SMAT: (a) experimental setup; (b) the localized plastic deformation in the surface layer induced by the impact of the ball.



(a) (b)

Fig. 2 The engineering stress-strain curves: (a) the as received 304SS and the single sheet of SMATed 304SS; (b) the as received 304SS and the three-layered co-rolled SMATed 304SS [11]

2. Experimental investigations and modeling of SMAT materials and process

There are numbers of experiments that are targeted at enhancing the mechanical properties of the SMATed materials so as to achieve better strength and ductility. Some experiments are conducted for better understandings on the mechanism of the SMAT process and the novel materials in order to further enhance the efficiency of this process. Some of the most recent and major works are introduced here.

2.1. Materials preparation

The targeted material subjected to most of the mechanical property tests, e.g. tensile property tests and nanoindentation, and parametric study of SMAT process is a single sheet of 304 SS of 1 mm thickness after SMAT. The type of balls used in SMAT was as described in ref. [13, 14]. The vibration frequency of the SMAT machine adopted was 20 kHz.

Another main material subjected to further studies, like study of fracture mechanism and examination of residual stress, is a three-layered warm co-rolled SMATed 304 SS. Two sheets of 304 SS of 1 mm thickness were first SMATed at 1 side of the surface. The co-rolling process was applied, as illustrated in Fig. 3 [11], where the NS layers are represented by shadow area. The co-rolling machine was preheated at 500 °C for 5 min. The stack specimen with two NS layers (illustrated in Fig. 3) was co-warm rolled by a single pass and then air cooled to room temperature.

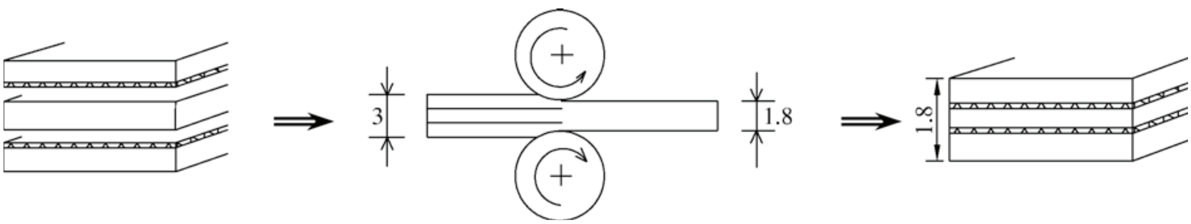


Fig. 3. Schematic illustrations of co-warm rolling process [11].

2.2. Experiments and models

After SMAT, the material obtained has the gradient structures with grain size varying from nanometers to micrometers from the surface layer down to core body. Nano-twins which are well-known to have great contribution on high strength and high ductility can be found at certain depths of the treated materials by the characterization from TEM images. Lately, the knowledge of the relations between the mechanical responses of materials subjected to SMAT, the resultant microstructures and the mechanical properties of the treated materials have been established. Some of the important studies are addressed here.

2.2.1. Optimization study of SMAT process

One of the recent works that has put forward to improve the SMAT process is the reveal of the relationship between the velocity of balls (i.e. strain-rate) and the resultant microstructure, nano-twins [12]. By adopting the high speed camera, the behaviors, esp. the velocity, of one single ball and different numbers of balls have been observed and hence the strain-rate which is the key factor to produce nano-twins [15], and the plastic strains can be estimated by theoretical analysis and computational models. A large number of samples treated by different number of balls have been characterized with TEM and examined with tensile property tests. Correlating the statistic obtained by TEM images on amount and sizes of nano-twins, the results of the tensile property tests and the estimated strain-rate obtained from computational model, the optimum velocity of balls which resulted in desirable strain-rate ($10^{-4}s^{-1}$) for production of effective nano-twins is obtained. This study has not only improved the efficiency of the SMAT process, but also provided a better understanding on the corresponding mechanism.

2.2.2. Characterization of plastically graded NS materials by nanoindentation

Nanoindentation has been applied to characterize the plastically graded NS materials obtained from SMAT [16, 17]. From the indentations at different depths of the materials, the distribution of yield stresses as well as the hardening coefficients can be obtained. These data points after fitting by bilinear curves demonstrate the decreasing yield stresses as well as increasing hardening coefficients from the treated surface to the core. On the other hand, the resultant hardening rate which is the product of yield stress and the hardening coefficient approaches a maximum value at the subsurface layer (around 50μm). This phenomenon was attributed to the great amount of nanoscale spaced deformation twins in the subsurface layer which can be observed from the TEM images. Combining all the stress-strain curves obtained from indentations along the thickness of this NS material with gradient structure, a constitutive model has been built to study the behavior of the plastically graded material in complex stress states. This computation scheme, the utilization of nanoindentation curves, proposed in this study is believed to be applicable for other materials with gradient structures as well.

2.2.3. Role of NS layer on layered composite materials and its model

A three-layered warm co-rolled SMATed 304SS has been reported of exhibiting high strength and good ductility and its fracture mechanism has been studied [11]. Hence, the particular role of NS layer in this layered composite material for enhancing the ductility was first discovered. It reported that the layered composite exhibits a special plastic deformation behavior, which involved in: (i) hardening, (ii) sliding, (iii) necking propagation, (iv) necking, and (v) cracking. In particular, the occurrence of sliding and necking propagation, which is believed to be the part taken by the NS layer, is a special deformation behavior of this layer-structured steel compared to the base material.

Later work explains this phenomenon further in relation to the particular role of NS layer, and a model has been constructed [18]. A computational framework based on cohesive finite element method (CFEM) has been adopted to analyze the process of damage initiation and evolution in the co-rolled SMATed 304SS with NS interface. It reported that the non-localized damage in the nanograined interface layer is found to be the toughening mechanism, and thus, it further confirmed that the brittle interface has a potential to lead to good ductility of the overall structure.

2.2.4. Role of residual stress

Lately, a precise set of automated measurement system, which combined Electronic Speckle Pattern Interferometry (ESPI) with hole-drilling method, has been built to measure residual stress. Firstly, the surface deformation relieved by hole-drilling is measured using ESPI, and subsequently, the residual stress is calculated from deformation field by data processing algorithms. Using the new-developed measurement system, the residual stress distributions in the three-layered warm co-rolled SMATed 304SS can be obtained. The results shown that the compressive residual stress is one of the key mechanisms for the enhancement and the extraordinary properties of layered nanostructured metallic stainless steel sheet.

3. Concluding remarks

SMAT is a sophisticated method for generating NS in metallic materials. Early works have already shown the superior strength of the SMATed materials possessed. The recent works extensively study the mechanism of SMAT process and the materials produced. The missing pieces of the knowledge on the relation between the process parameters, mechanical response of the treated materials, the corresponding microstructures and accordingly the mechanical properties have been collected. As better understandings have been gained on the effects of the process parameters, the SMAT process can be better controlled and hence its efficiency can be further enhanced. The treated materials which obtain higher strength as well as higher ductility can be expected and the latest experimental results have further proved this expectation.

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