Materials Chemistry and Physics 125 (2011) 418–426

Contents lists available at ScienceDirect

Materials Chemistry and Physics

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

Effect of surface mechanical attrition treatment (SMAT) on microhardness, surface roughness and wettability of AISI 316L

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ARTICLE INFO

Article history:
Received 28 May 2010
Received in revised form 19 October 2010
Accepted 24 October 2010

Keywords:
Surface mechanical attrition treatment
Microhardness
Roughness
Wettability
AISI 316L

ABSTRACT

Surface roughness and wettability are among the surface properties which determine the service lifetime of materials. Mechanical treatments subjected to the surface layer of materials are often performed to obtain the desired surface properties and to enhance the mechanical strength of materials. In this paper, the surface microhardness, roughness and wettability of AISI 316L stainless steel resulting from surface mechanical attrition treatment (SMAT) are discussed. The SMAT was conducted with various processing parameters, including the duration of treatment, the number and diameter of milling ball, and the motor speed of the SMAT machine. The result indicates an increasing surface microhardness due to the SMAT. A harder surface is yielded by the SMAT with a longer duration, a bigger and a larger number of milling balls, and a higher vibration frequency. The SMAT also creates craters on the steel surfaces which correspond to the increasing roughness from 0.046 μm to the values in ranging from 0.681 to 0.909 μm. The change on the surface roughness by the SMAT does not only depend on the duration of treatment, but also the other processing parameters. In addition, the wettability of AISI 316L surface slightly increases by the SMAT as seen on the decreasing droplet contact angle from 88.6° to the values ranging from 74.4° to 87.0°. Such a droplet contact angle reduction is related to the increasing surface roughness after the SMAT. In conclusion, this study reveals the possibility of the SMAT to be used for surface properties optimization in addition to the strength enhancement of stainless steel.

1. Introduction

Surface roughness and wettability are crucial in bioadhesion [1–5]. A rough and hydrophilic surface is favorable for the adsorption of specific proteins which initiates the sequences of bone cells development on implant [2]. This may subsequently lead to the formation of a strong and stable bonding between the implant and the bone tissue [1,3,6]. In contrary, bacteria are more easily removed from a smooth and a hydrophobic implant surface [4–6].

Two methods are currently used for controlling the roughness and wettability of metal surfaces, i.e. non-deforming [1,7–9] and deforming [1,10–14] methods. Polishing [7,8], machining [1], acid-etching [1,9], and anodizing [1] are among the non-deforming methods, whereas sandblasting [1,10,11], and shot peening [12–14] creates a rough and hydrophilic surface by deforming the surface by shots or particles impacts. As the consequence, not only the surface structure and roughness, but also the strength of metals changes due to the formation of fine grains, residual stress, and martensite phase in the surface layer by those treatments [1,14–16].

Surface mechanical attrition treatment (SMAT) has been also developed recently to increase the strength of metallic materials by means of shots or milling balls impacts. However, it is different in some aspects with shot peening. The SMAT utilizes larger spherical balls (>1 mm) than those in the shot peening (0.2–1 mm). The milling ball velocity in the SMAT is around 1–20 $m\,s^{-1}$ and directed randomly to the treated surface. In contrary, the shot or particle velocity in the shot peening is typically about 100 $m\,s^{-1}$ and directed normally to the treated surface [17]. The SMAT uses a mechanical vibration instead of a high power ultrasound as in the ultra-sonic shot peening (USSP) for generating repetitive impacts of milling balls on the treated surface [15,16,18].

AISI 316L becomes one of the most widely used steel for engineering and medical applications due to its excellent properties in corrosion and oxidation resistance [19] and biocompatibility [13,20]. The recent studies have already shown the prominences of SMAT to increase the tensile and bending strength, the thermal sta-

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doi:10.1016/j.matchemphys.2010.10.038

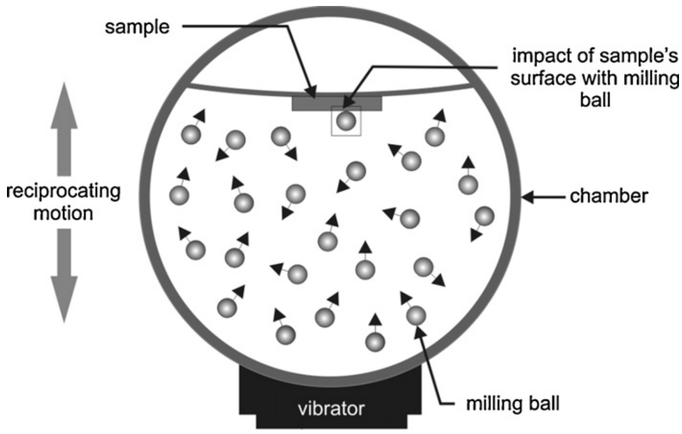

Fig. 1. Illustration of the SMAT principle.

bility [21] and the fatigue life [22] of AISI 316L although a decrease in the corrosion resistance is also revealed [23]. However, the effect of the SMAT on the surface properties (e.g. surface roughness and wettability) of AISI 316L has never been investigated. In this study, the roughness and wettability of AISI 316L after the SMAT are studied. The changes on surface microhardness are also presented to confirm the effect of the SMAT in this study with the previous ones [21,22]. Several processing parameters such as the duration, the number and the size of milling balls, and the vibration frequency during the SMAT are also evaluated in order to look at the possibility of the SMAT parameter optimization for the surface managements of AISI 316L.

2. Materials and methods

2.1. Sample preparation

Samples were prepared from AISI 316L plate with a dimension of 100 mm × 50 mm × 4 mm. The samples chemical compositions (wt%) are 0.0316 C, 24.3038 Cr, 10.9653 Ni, 1.7477 Mo, 1.2369 Mn, 0.4360 Si, 0.8637 Cu, and 0.0002 S. All samples were polished prior to the SMAT to obtain surfaces with a uniform roughness. The polishing treatment was conducted using a custom-built machine with a pin on disc configuration. The pin was a steel plate mounted on resin, whereas the rotating disc was a metal covered by an abrasive paper. The minimum surface roughness as obtained by polishing machine was R_a = 0.046 μm, subsequently the roughness of all samples prior to the SMAT is established into this value.

2.2. Surface mechanical attrition treatment

The principle of the SMAT has been introduced previously [17] and is shown schematically in Fig. 1. During the SMAT, the sample was affixed on the top side of a tubular chamber whose length and diameter are 150 and 80 mm, respectively. A crankshaft with an eccentricity of 10 mm was used for transmitting 1.5 HP from an electric motor by which the SMAT chamber was vibrated. Such a vibration yielded a multiple impact of the treated surface with the milling balls.

In this study, the SMAT was conducted with various processing parameters, i.e. the duration of treatment, the diameter and the number of milling balls, and the motor speed of the SMAT machine. The details of each SMAT parameter in this experiment are described below.

(1) Variation on the treatment duration
The samples were treated for 5, 10, 15, and 20 min using 250 stainless steel balls whose diameter of 4.76 mm and with a motor speed of 1400 rpm.
(2) Variation on the number of milling ball
The samples were treated for 15 min using 125, 250, and 375 stainless steel balls whose diameter of 4.76 mm in and with a constant motor speed of 1400 rpm.
(3) Variation on the motor speed
The vibration frequency changes with the motor speed of the SMAT machine. In this experiment, the motor speed was 952 and 1400 rpm, and 250 stainless steel balls with a diameter 4.76 mm were used for 15 min of treatment.
(4) Variation on the milling ball diameter
The samples were treated for 15 min using 250 stainless steel balls whose diameter of 3.18, 4.76, and 6.35 mm and with a constant motor speed of 1400 rpm.

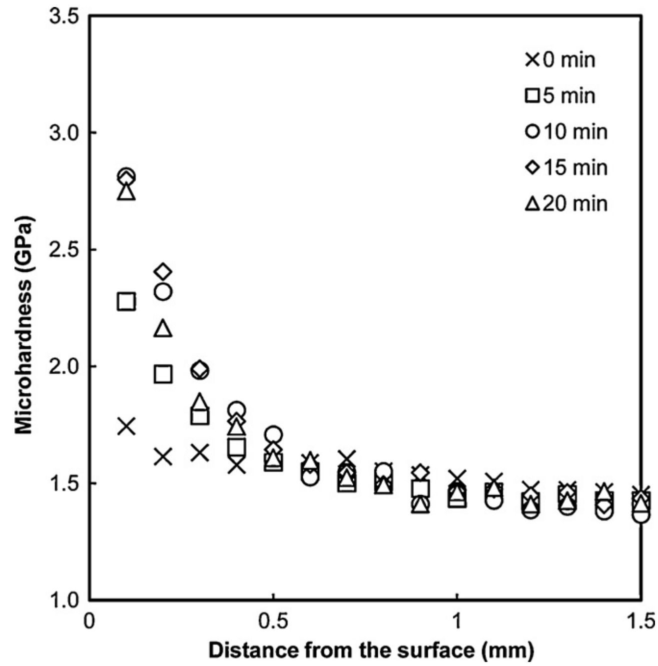

Fig. 2. Effect of the duration on the microhardness.

2.3. Microhardness measurement

The effect of the SMAT can be simply observed on the distribution of microhardness over the cross sectional area of the samples [21,22]. For this purpose, each sample was cut laterally after the treatment to expose its cross-sectional area at which the measurement was conducted. Some pre-treatments were performed, including sample mounting, grinding, and polishing the sectioned surface. The microhardness at several points closer to the surface layer was measured using a microhardness tester (Buehler, USA) with an indenting load of 4.9 N.

2.4. Surface structure observation and roughness measurement

The surface structures were observed using a microscope (Olympus, Japan) to identify the traces on the surface as created by the impact of milling balls. The samples surface roughness was quantified using a contact stylus profilometer (Surfcom 120A, Advanced Metrology System, UK). The measurement was conducted on 30 different locations to obtain the arithmetic medium value (R_a) of the samples. All samples were cleaned up using 70% ethanol, rinsed in distilled water, and dried prior to the observation and measurement.

2.5. Wettability measurement

The surface wettability was quantified through a sessile drop test to obtain the droplet contact angle on each sample. The treated samples were also cleaned up using 70% ethanol, rinsed in distilled water, and dried before the measurement. A distilled water droplet was deposited three times at five different locations on the surface of each sample. The static droplet on sample's surface was recorded using a high speed camera (MEMRECAM C3, NAC Image Technology, USA) by which the droplet contact angle analysis was then carried out.

3. Results

3.1. Microhardness

The microhardness distributions across the samples sectional areas are shown in Figs. 2–5. The SMAT increases microhardness by approximately two times at a distance of 0.1 mm from the surface. The microhardness of the SMAT samples gradually decreases and approaches the values for the control sample (±1.5 GPa) at a distance of larger than 0.5 mm from the surface.

The samples microhardness distributions after the SMAT with various processing duration are depicted in Fig. 2. The longer SMAT duration, the higher surface microhardness is. However, further enhancement does not occur after 10 min of treatment. Fig. 3 shows