Surface & Coatings Technology xxx (2013) xxx–xxx

Contents lists available at SciVerse ScienceDirect

Surface & Coatings Technology

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

Effect of surface mechanical attrition treatment (SMAT) on pack boronizing of AISI 304 stainless steel

T. Balusamy [a,b], T.S.N. Sankara Narayanan [a,c,*], K. Ravichandran [b], Il Song Park [c], Min Ho Lee [c,*]

[a] CSIR-National Metallurgical Laboratory, Madras Centre, CSIR Complex, Taramani, Chennai-600 113, India
[b] Department of Analytical Chemistry, University of Madras,Maraimalai (Guindy) Campus, Chennai-600 025, India
[c] Department of Dental Biomaterials, School of Dentistry, Chonbuk National University, Jeonju 561-756, South Korea

ARTICLE INFO

Article history:
Received 18 December 2012
Accepted in revised form 25 April 2013
Available online xxxx

Keywords:
Surface mechanical attrition treatment (SMAT)
Boronizing
Iron borides
Alloy borides
Diffusion
Kinetics

ABSTRACT

The influence of surface mechanical attrition treatment (SMAT) on pack boronizing of AISI 304 stainless steel (304 SS) is addressed. SMAT of 304 SS was performed using 8 mm Ø 316L stainless steel balls for 60 min. Untreated and SMATed 304 SS samples were pack boronized by single stage (at 1223 K for 1, 3 5 and 7 h) and duplex (973 K for 1 h and 1223 K for 1 h) treatments. SMATed 304 SS increased the kinetics of boron diffusion, enabled the formation of a higher volume fraction of alloy borides and increased the hardness of the borided layer. Duplex treatment increased the case depth than the single stage treatment. The findings of this study suggest that SMAT can be used as an effective pretreatment for boronizing of 304 SS.

1. Introduction

Boronizing is a thermo-chemical surface treatment process, which involves diffusion of boron atoms into the surface of metal/alloy to produce a layer of borides of the corresponding metal/alloying elements [1,2]. It is widely employed to improve the hardness, tribological properties and corrosion resistance of ferrous alloys [3–9]. Boronized stainless steels find application in food and chemical industries, nuclear power plants and, biomedical applications [10–15]. Various types of boronizing, namely, pack, paste, electrolytic, laser, etc., have been developed to meet the challenging needs of various industries [16–21]. Among them, pack boronizing assumes significance following its easy adaptability in process industries. Pack boronizing is usually performed using a powder mixture consisting of an active ingredient (B_4C), an activating agent (KBF_4) and a diluent (SiC) at 1173–1273 K for a few hours depending on the desired case depth. During boronizing, the case depth, phase contents, hardness and tribological properties of the resultant boronized layer are primarily determined by the surface reactions and the kinetics of boron diffusion. Improving the surface reactivity and accelerating the diffusion of boron is a challenging issue and calls for suitable process modifications [22].

It has been shown that in nanocrystalline and ultra-fine grained (UFG) materials, the presence of large number of grain boundaries and triple junctions could act as fast atomic diffusion channels [23,24]. In the past decade, diffusion behavior in nanostructured or UFG materials produced by severe plastic deformation (SPD) has become an attractive topic, since SPD processing is a promising route for producing bulk nanostructured materials with enhanced properties [25,26]. Surface mechanical attrition treatment (SMAT) is a surface SPD method that enables nanocrystallization at the surface of various metallic materials [27–34]. SMAT enhanced the kinetics of diffusion during nitriding, aluminizing, chromizing, diffusion zinc coatings and diffusion of nickel in copper [35–40]. Several reasons have been attributed for the observed increase in the kinetics of diffusion of the active elements. The formation of a gradient microstructure, pronounced non-equilibrium state of interfaces, ~30% excess free energy of the high angle grain boundaries have been reported to be the major reasons for the observed increase in diffusion of Ni by ~4 orders of magnitude on SMATed copper [40]. Wang et al. [41] have observed an enhanced diffusivity of Cr in nanocrystalline Fe sample produced by SMAT and correlated it to the presence of a large volume fraction of non-equilibrium grain boundaries with high density of dislocations and considerable amount of triple junctions. Nitriding, aluminizing and chromizing are relatively low temperature processes when compared to boronizing. Hence, materials subjected to SMAT could maintain their nanostructured surface layer. In addition, the increase in grain size during these processes is rather limited to cause any significant influence on the kinetics of diffusion of the corresponding elements. However, the temperature and treatment time employed

* Corresponding author. Department of Dental Biomaterials, School of Dentistry, Chonbuk National University, Jeonju 561-756, South Korea. Tel./fax: +82 63 270 4040.
E-mail addresses: tsnsn@rediffmail.com (T.S.N. Sankara Narayanan), lmh@jbnu.ac.kr (Min Ho Lee).

0257-8972/$ – see front matter
http://dx.doi.org/10.1016/j.surfcoat.2013.04.053

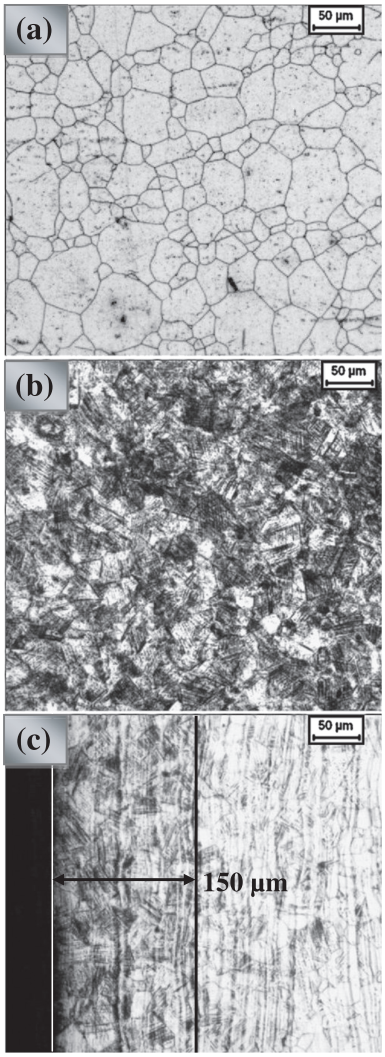

Fig. 1. Optical micrographs of untreated and SMATed AISI 304 SS taken at (a, b) the surface and (c) cross section: (a) untreated; and (b, c) SMATed using 8 mm Ø 316L SS balls for 60 min.

for boronizing of most ferrous alloys are of the order of 1173–1273 K for a few hours and, hence it is very difficult to realize the benefits of nanostructuring at such conditions. This has also been addressed in our earlier paper on the effect of SMAT on boronizing of EN8 steel [42]. The surface nanocrystallization by SMAT offers the benefit of formation of borided layers at relatively lower temperatures. Xu et al. [43] have shown that boronizing of SMATed H13 steel could be achieved at 973 K for 8 h. According to Yang et al. [44], the formation of large number of grain boundaries with various kinds of non-equilibrium defects induced during SMAT enables an increase in kinetics of plasma boronizing of H13 steel at 853 K for 4 h. In our earlier study [42], we have shown that it is possible to get a reasonably thick boronized layer on SMATed EN8 steel at 923 K for 7 h. However, such a long processing time is not practicable for many industrial components. Boronizing of stainless steels has been well studied and the details were reported elsewhere [12,15,45–50]. Jauhari et al. [48] have observed an increase in case depth of boronized layer formed on duplex stainless steel subjected to super plastic deformation. However, the effect of SMAT on boronizing of AISI 304 stainless steel (304 SS) is not studied previously. Since boronizing of 304 SS requires a higher temperature of the order of 1223 K, it would be interesting to know to what extent the surface nanocrystallization generated by SMAT will be useful in promoting the kinetics of diffusion of boron. Duplex treatment is considered as one of

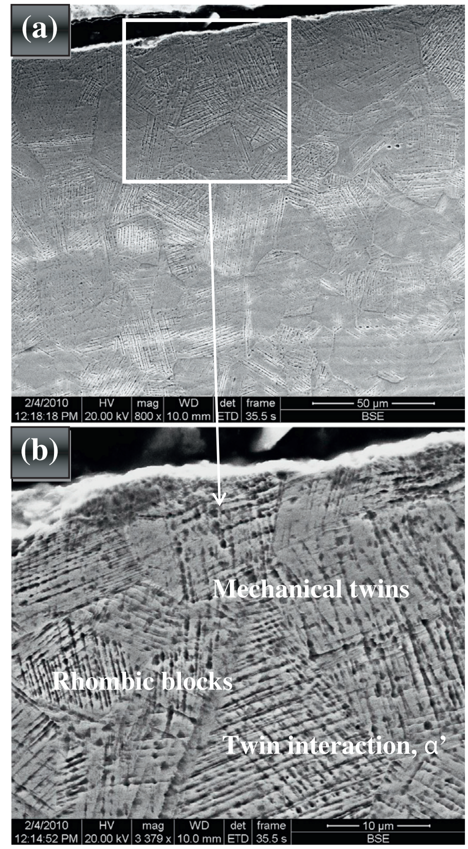

Fig. 2. Scanning electron micrographs taken at the cross section of AISI 304 SS subjected to SMAT using 8 mm Ø 316L SS balls for 60 min.

the possible modifications of surface treatment by chromizing and boronizing. It is shown to be beneficial in increasing the kinetics of chromizing of low carbon steel [51] and H13 steel [38] that results in the formation of a much thicker chromized surface layer. Further, it is found to be effective in increasing the boron diffusion kinetics and formation of a dense and compact boronized layer with a relatively higher thickness on EN8 steels [42]. Hence, it is worthwhile to verify the effectiveness of duplex treatment. The present paper aims to address the effect of SMAT on pack boronizing of 304 SS and to compare the effectiveness of single stage and duplex treatments.

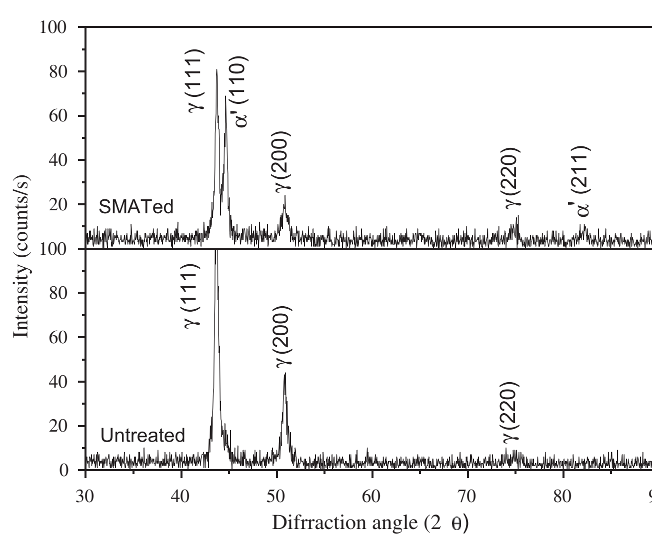

Fig. 3. X-ray diffraction patterns of untreated AISI 304 SS and those subjected to SMAT using 8 mm Ø 316L SS balls for 60 min.