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Enhanced surface properties of austenitic stainless steel by electropulsing-assisted ultrasonic surface rolling process

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ABSTRACT

The present work reports the experimental observations of surface property enhancement for austenitic stainless steel treated by electropulsing-assisted ultrasonic surface rolling process (EP-USRP). Compared with the original ultrasonic surface rolling process (USRP), the introduction of electropulsing can facilitate the surface cracks healing, and alter the cross-sectional micro-hardness gradient distribution within the surface strengthened layer, i.e. significantly gaining higher surface hardness or greater impact depth under the different experimental parameters. Refined grain and enhanced plastic deformation caused by electropulsing are likely the primary reason for the observed phenomena.

1. Introduction

Ultrasonic surface rolling process (USRP), which utilizes the combination of static extrusion and dynamic impact is a novel surface nanocrystallization technology based on severe plastic deformation (SPD) [1]. In USRP, an ultra-hard processing tip is employed to roll the material surface under a static force [2]. Meanwhile, dynamic impact is applied to the surface through the tip by ultrasonic apparatus in the normal direction [1,2]. Therefore, USRP can make bulk materials with gradually hardening surface strengthened layer by SPD [3] due to grain refinement [4,5] and dislocation multiplication [6]. Nowadays, USRP is more and more frequently used to improve the fatigue, corrosion, friction and wear resistance performances of the mechanical components [1,2,7–9]. But on the down side, remarkable hardening of surface strengthened layer induced by SPD [6,10] is also an extreme obstruct for the further plastic deformation and strengthening inside of the metal. And there is no significantly improvement to be continued in top surface strengthened layer in the subsequent process due to its existing high hardness. The internal factors of the limited surface hardening and process impact depth resulted by the above mentioned are immobile dislocations accumulation and restricting deformation limit produced by USRP.

Electropulsing, as an advanced external field processing technology for metallic material can affect its plasticity [11–16], recrystallization [17–19], phase transformation [20,21], structure evolution [22–26], casting microstructure [27–29] and fatigue life [21,30,31]. Employment of electropulsing in the plastic processing of metallic material can reduce the deformation resistance [14,15], and improve the surface quality of components dramatically [15,32] because of the remarkable reduction in work hardening and less amount of defects in materials based on electropulsing-accelerated phase transformation, dislocation mobility and atom diffusion. Rongshan Qin et al. utilized electropulsing to control the microstructure of steels towards a state that possesses favorable physical, mechanical and chemical properties with appropriate electropulsing parameters [13]. H. Conrad et al. proposed that the high mobility of dislocations due to the electric current played an important role in such effects via the studies on the influence of electropulsing to the recrystallization of metallic material [33–35]. Our previous study on electropulsing application in ultrasonic striking treatment of Ti–Al–V alloy indicates that electropulsing can dramatically improve the micro-hardness of the refined surface layer comparing with the original ultrasonic-shocked situation [36]. Moreover, the materials ductility under electropulsing treatment is noticeably improved while sacrificing the strength slightly [37]. But up to now, little has been done on the effects of electropulsing in USRP.

In the present work, a method called electropulsing-assisted ultrasonic surface rolling process (EP-USRP) is proposed to target the shortcoming in USRP. As a consequence, a strengthened layer with a higher surface hardness or a greater impact depth was achieved under the

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different experimental parameters in 304 austenitic stainless steel. Such observations reveal a new potential mechanism and may provide an alternative way to enhance surface properties of metallic material to a higher degree.

2. Experimental procedures

The as-received alloy 304 austenitic stainless steel was treated via a solid-solution treatment prior to being cut into pole-shaped samples, and then processed by turning to the specimens with a dimension of Φ16.8 mm × 150 mm to ensure obtaining the uniform surface morphology characteristics as much as possible. The turning parameters were chosen as follows: cutting speed was 40 m min^{-1}, feeding rate was 0.1 mm rev^{-1}, depth of cut was 0.6 mm. The tool angles were set as follows: rake angle was 6°, clearance angle was 6°, principal cutting edge angle was 95°, tilt angle was 6°, and the nose curvature radius was 0.2 mm. The chemical composition in wt.% of the steel was found to be 0.03 C–18.5 Cr–2.0 Mn–9.5 Ni–1.0 Si–0.03 S–0.045 P and balance Fe.

The EP-USRP experiments were carried out on a self-built platform based on a conventional lathe. A schematic diagram for EP-USRP is shown in Fig. 1. A scrollable rolling tip having a hardness of 80 HRC, a surface roughness of Ra 0.1 μm and a radius of curvature of 7 mm equipped with an ultrasonic apparatus was used for both USRP and EP-USRP experiments. The basic parameters were as follows: rolling line speed was 24 m min^{-1}, feeding rate was 0.1 mm rev^{-1}, static force was 700 N, vibration amplitude was 8 μm, vibration frequency was 30,000 Hz and repeated processing number was 5. For EP-USRP experiments, the continuous electric pulses with a sharp waveform were applied to the specimen by using a self-designed power generator. The pulse width was 60 μs, and pulse frequency was 600 Hz. The Root–Mean–Square current densities J_e were 0.62 A mm^{-2}, 0.91 A mm^{-2}, 1.12 A mm^{-2} and 1.34 A mm^{-2}, the corresponding maximum current densities J_m were 4.73 A mm^{-2}, 7.04 A mm^{-2}, 8.01 A mm^{-2} and 9.65 A mm^{-2} in order. For each EP-USRP experiment, the electropulsing was used through the entire process, whilst the ultrasonic impact treatment was only started up when the surface temperature of specimen reached an equilibrium value. The L-G 8 guide rail oil was used in process for cooling and lubricating.

The surface temperature on specimen was monitored by using a K type surface thermocouple. The axial surface roughness of each specimen was evaluated by a Surtronic S25 contact-type surface roughness tester. The cross-sectional Vickers micro-hardness within surface layer was measured by using a HVS-1000B micro-Vickers hardness tester employing a 100 g load for a dwell time of 15 s. KH-7700 digital microscope was used to observe micro-morphology on specimen surface. Hitachi S4800 scanning electron microscope (SEM) and JOEL-JEM-2100 transmission electron microscope (TEM) were utilized to analyze cross-sectional microstructure in specimen surface layer.

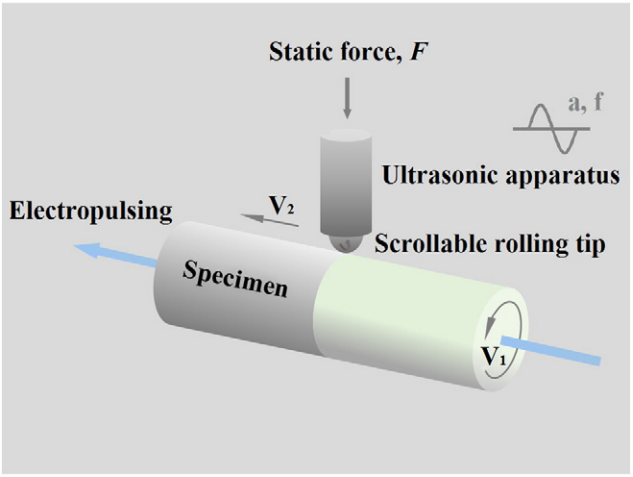

Fig. 1. A schematic illustration of the EP-USRP setup.

3. Results and discussion

As depicted in Fig. 2, the Joule thermal effect of electropulsing causes a rise of the surface temperature on specimen. The larger pulse current density, the higher surface equilibrium temperature is presented [38]. The axial surface roughness on specimens after USRP and EP-USRP reach about Ra 0.2 μm, showing a remarkable decline compared with Ra 1.2 μm of the turning surface. For these specimens treated by EP-USRP, the axial surface roughness slightly decreased with the increasing of pulse current density. However, some obvious morphology differences at micro-level can be noticed in Fig. 3. After treatment, the USRP surface (Fig. 3b) shows a better quality than turning surface (Fig. 3a), but there are many micro cracks and defects on the surface. Undoubtedly, these will potentially become crack sources, and result in the serious negative impact on mechanical components fatigue life [39–41]. This situation has been significantly improved when electropulsing was introduced. In EP-USRP, the healing of surface cracks can be observed and become more remarkable with the increase of pulse current density (Fig. 3c–f). The specimen treated by EP-USRP at J_e of 1.34 A mm^{-2} gives an excellent surface morphology with few cracks and defects (Fig. 3f). The existing studies indicate that USRP can reduce surface roughness and improve micro-hardness [2]. However, the processed surface could deteriorate to a certain extent because of common shear deformation and local fatigue damage, which favors the decrease of deformation resistance [42]. But in the present case, the applied electropulsing can facilitate micro cracks healing and reduce the amount of defects to further improve the surface quality via enhancing mobility of dislocation, atomic migration and plastic deformation ability in surface layer of the materials [23,27,36,43].

The variations of cross-sectional micro-hardness gradient distribution within the surface strengthened layer induced by electropulsing are presented in Fig. 4. It can be seen that there is a remarkable improvement in surface hardness for all specimens after treatment. Whilst the distinct differences in both surface hardness and impact depth of the strengthened layer between USRP and EP-USRP also exist. For USRP, the surface hardness increased from the initial state of 190 HV to 385 HV. When electropulsing is employed for EP-USRP, surface hardness declines after an initial increase as the pulse current density rising, but the impact depth of strengthened layer increases. At J_e of 0.91 A mm^{-2}, the surface hardness reaches 423 HV, and the cross-sectional micro-hardness show

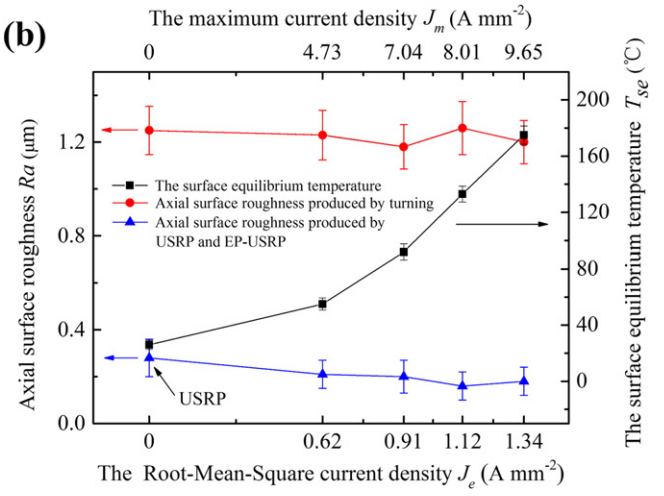

Fig. 2. Variations of surface equilibrium temperature and the axial surface roughness on specimens before and after treatment.