RESEARCH ON PULSED CURRENT-ASSISTED ROLLING FORMING AND MICROSTRUCTURE–PROPERTIES OF PURE TITANIUM ULTRA-THIN STRIPS

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Pure titanium ultra-thin strips have extensive applications in the aerospace, new energy, and electronic communication industries. However, conventional cold rolling processes for producing pure titanium ultra-thin strips face challenges such as significant work hardening, limitations on rolling thickness and excessive residual stress. In this study, a pulse current-assisted rolling process was employed, utilizing the synergistic effects of the thermal and non-thermal effects of the pulse current to improve formability. Using TA1 pure titanium ultra-thin strips as the subject, an experimental platform was established on a twelve-high rolling mill to investigate the effects of current parameters on the material's rolling deformation behavior, microstructure and mechanical properties. The results indicate that, compared to conventional cold rolling, pulse current-assisted rolling can effectively reduce deformation resistance and increase the rolling reduction rate; the pulse current promotes dislocation slip and dynamic recovery, thereby reducing work hardening. Under equivalent deformation conditions, the pure titanium ultra-thin strips produced by this process maintain high strength while exhibiting an elongation after fracture approximately 15%~35% higher than that of conventionally cold-rolled strips, demonstrating a favorable strength-ductility balance. Pulse current-assisted rolling offers a new technical approach for the production of high-performance pure titanium ultra-thin strips.

KEYWORDS: PURE TITANIUM ULTRA-THIN STRIPS – PULSED CURRENT-ASSISTED ROLLING – DEFORMATION BEHAVIOR – MICROSTRUCTURE – MECHANICAL PROPERTIES

INTRODUCTION

Commercially pure titanium (CP-Ti) is characterized by low density, high specific strength, excellent corrosion resistance, and good biocompatibility, and has therefore found important applications in aerospace, fuel cells, precision electronics, and microscale heat-exchange structures. With the continuing trend toward lightweight and miniaturized components, titanium products are evolving from conventional sheets and strips toward ultrathin strips at the micrometer scale. Such pure titanium ultra-thin strips are promising for fuel-cell bipolar plates, precision heat-exchange components, and microscale functional devices. However, as the strip thickness decreases, the number of grains participating in through-thickness deformation accommodation is reduced, while the fraction of surface grains increases, further limiting the uniformity of plastic deformation and forming stability [1]. TA1 commercially pure titanium has a typical hexagonal close-packed (HCP) crystal structure at room temperature, and its plastic deformation is mainly accommodated by dislocation slip and mechanical twinning. With increasing cold-rolling strain, dislocations progressively accumulate near grain boundaries, twin boundaries, and other slip barriers, resulting in increased intragranular orientation gradients and stored deformation energy, thereby intensifying work hardening and reducing ductility [2].

Electropulse-assisted plastic processing provides a promising route for improving the formability of difficult-to-deform metals. Previous studies have shown that electric current can reduce the flow stress, enhance ductility, and regulate microstructural evolution, with the underlying mechanisms generally involving Joule heating and current-related non-thermal effects [3]. For commercially pure titanium, Li et al. reported from electrically assisted tensile tests of TA1 that increasing current density reduced the flow stress and work-hardening capacity, while promoting dislocation slip and suppressing deformation twinning [4]. Zhou et al. further found that electropulsing treatment promoted dislocation rearrangement and annihilation as well as the formation of low-angle grain boundaries in ultrathin cold-rolled TA1, and could induce recrystallization under appropriate electropulsing conditions [5]. Nevertheless, most existing studies have focused on electrically assisted tension, post-deformation electropulsing treatment, or titanium materials of conventional thickness. Studies on the synchronous coupling of pulsed electric current with multi-roll rolling of titanium ultrathin strip remain relatively limited.

Therefore, 100 μm-thick TA1 pure titanium ultrathin strips were selected as the experimental material, and pulsed-current-assisted rolling experiments were conducted on a twelve-high rolling mill. By comparing the microstructural characteristics and mechanical properties of room-temperature rolled specimens with those of electrically assisted rolled specimens under different current amplitudes, the effects of pulsed current on the microstructure and mechanical properties of pure titanium ultrathin strips were investigated, and the mechanism by which pulsed current improves the ductility of ultrathin strips was elucidated.

MATERIAL AND TEST PROCEDURE

The starting material for the rolling experiments was an annealed TA1 pure titanium ultrathin strip with a thickness of 100 μm. The rolling experiments were conducted on a twelve-high precision rolling mill. The mill was electrically insulated and modified to establish a pulsed-current-assisted rolling platform for pure titanium ultrathin strips, as schematically shown in Fig. 1. Using this platform, electrically assisted rolling tests can be performed under different pulsed-current conditions, while conventional room-temperature rolling can be carried out by switching off the pulsed power supply.

A direct-current square-wave pulse was applied with a frequency of 100 Hz and a duty cycle of 10%. Pulsed-current-assisted rolling tests were conducted at current amplitudes of 6, 7, and 8 A. The same rolling speed as well as front and back tensions were maintained for all tests. The roll gap was continuously adjusted to ensure that the electrically assisted rolled specimens obtained under different current conditions had the same final thickness. Subsequently, the pulsed power supply was switched off, and conventional room-temperature rolling was performed at the same rolling reduction. The detailed rolling parameters are listed in Table 1.

The rolled ultra-thin strips were measured using a micrometer with a resolution of 0.1 μm. The measured exit thickness was approximately 80 μm, corresponding to a rolling reduction of about 20%. The mechanical properties along the rolling direction (RD) were evaluated at room temperature using an INSTRON 5969 universal testing machine at a tensile speed of 0.5 mm/min. The tensile specimens were prepared in accordance with ASTM E8/E8M-15 for room-temperature tensile testing, with a gauge length of 25 mm and a width of 6 mm. Microstructural characterization of the specimens was carried out using a JEOL IT500 scanning electron microscope (SEM) equipped with an electron backscatter diffraction (EBSD) system.

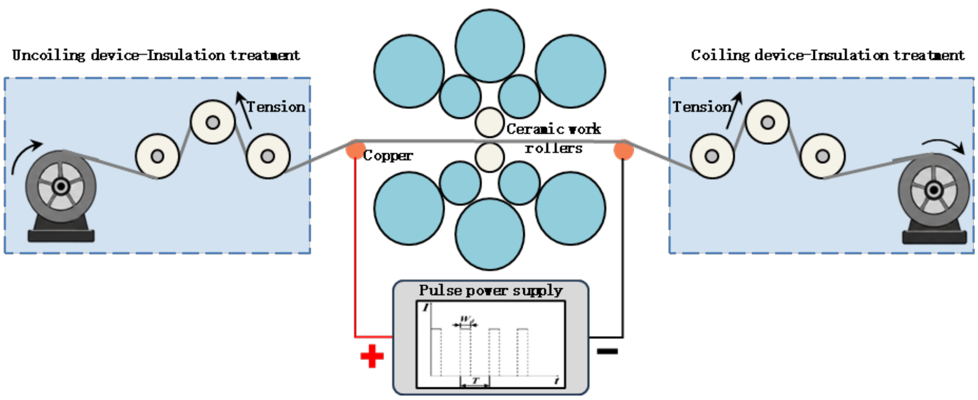

Fig.1 - Schematic diagram of pulsed current-assisted ultra-thin strip rolling test

Tab. 1 - Detailed parameters of pulsed current-assisted rolling tests

Specimen name	Electro-pulsing parameters	Temperature（℃）	Rolling Speed（mm/s）	Front and back tensions（N）
R0	0	25	5	60
E1	6 A-10%-100 Hz	233		
E2	7 A-10%-100 Hz	272		
E3	8 A-10%-100 Hz	329		

RESULTS AND DISCUSSION

Rolling deformation behavior

Figure 2 shows the changes in rolling force and relative roller gap setting values corresponding to different pulse currents under the same rolling deformation conditions. The roller gap setting value when the room-temperature rolled specimen R0 reaches an exit thickness of approximately 80 μm is used as the reference, and its relative value is defined as 0. As shown in the figure, as the pulse current increases, the roll gap setting for electrically assisted rolling increases by 0.014, 0.015, and 0.017 mm, respectively, compared to room-temperature rolling, while the rolling force decreases by 6.25%, 9.38%, and 15.62%, respectively. The results indicate that, for the same rolling deformation, room-temperature-rolled specimens require greater mechanical reduction than electrically-assisted-rolled specimens, and the rolling force of the electrically-assisted-rolled specimens is lower than that of the room-temperature-rolled specimens..

This behavior can be attributed, on the one hand, to Joule heating, which enhances the thermally activated motion of dislocations, and, on the other hand, to the possible promotion of dislocation unpinning, migration, and rearrangement by the pulsed current, thereby alleviating dislocation pile-up and work hardening [6]. As the deformation resistance of the material decreases, the rolling force is reduced accordingly, accompanied by a decrease in the elastic deformation of the roll system. Therefore, the same degree of mechanical screw-down as that required for room-temperature rolling is no longer necessary to achieve the same exit thickness. These results demonstrate that, compared with conventional cold rolling, pulsed-current-assisted rolling can effectively reduce the mill load and material deformation resistance, while providing additional processing margin for further increasing the single-pass reduction capability.

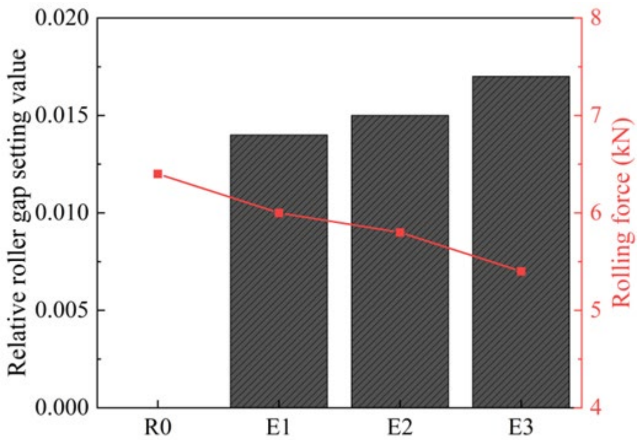

Fig.2 - Changes in relative roller gap setting value and rolling force under different pulse currents

Tensile properties

The stress–strain curves of the rolled specimens were compared, and the corresponding yield strength (YS), ultimate tensile strength (UTS), and elongation (EL) were selected as the mechanical property parameters to evaluate the effect of pulsed-current amplitude on the mechanical behavior of the electrically assisted rolled specimens. Figure 3 presents the mechanical properties of the room-temperature rolled specimen and the specimens rolled under different current amplitudes at the same rolling deformation. As shown, the stress–strain curve of the R0 room-temperature rolled specimen exhibits the highest stress level and the shortest strain range, corresponding to the highest YS and UTS values of 422.1 MPa and 432.3 MPa, respectively, and the lowest EL of 6.6%.

In contrast, the YS and UTS of all electrically assisted rolled specimens are lower than those of the room-temperature rolled specimen, whereas their EL values are higher. The current amplitude has a pronounced effect on the mechanical properties of the electrically assisted rolled specimens. With increasing pulsed current, both YS and UTS gradually decrease, while EL increases continuously, with improvements of 16.7%, 28.5%, and 36.4%, respectively. These results indicate that, under the same rolling deformation, the electrically assisted rolled specimens exhibit a lower degree of work hardening and improved plastic deformability.

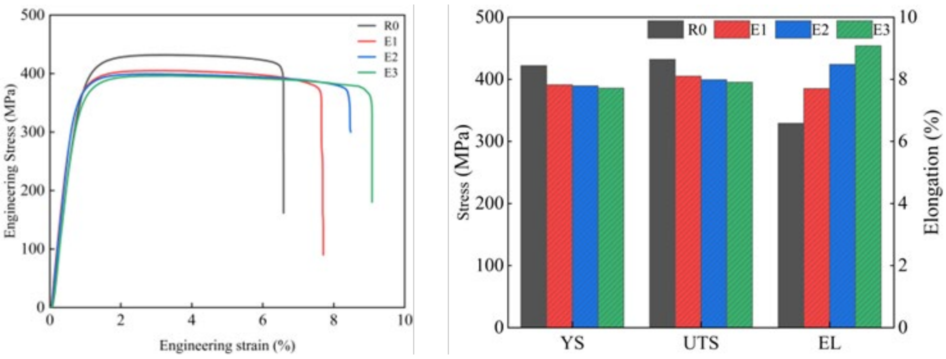

Fig.3 - Mechanical properties of conventional rolled specimen and electrified rolled specimens under different current magnitudes

Microstructure evolution

Figure 4 shows the kernel average misorientation (KAM) distributions of the room-temperature rolled specimen and the electrically assisted rolled specimens. The KAM maps can be used to characterize the distributions of dislocation density and local strain within the microstructure. With increasing pulsed current, the intragranular local misorientation generally decreases, with the average KAM value decreasing from 1.13° to 0.94°, 0.92°, and 0.76°, respectively. This indicates that the local lattice distortion caused by dislocation accumulation during rolling is progressively reduced.

The geometrically necessary dislocation (GND) density was further estimated using $\rho_{GND} = 2\theta_{KAM} / (Xb)$, where X=0.2 μm and b=0.295 nm [7]. The estimated GND densities of the R0, E1, E2, and E3 specimens were approximately 6.69×10^{14}, 5.56×10^{14}, 5.44×10^{14} and 4.50×10^{14} mm^{-2}, respectively. Compared with the R0 specimen, the GND density of the E3 specimen decreased by approximately 32.7%, indicating that the pulsed current promoted dislocation migration, rearrangement, and partial annihilation during rolling, thereby reducing the intragranular orientation gradient and the degree of stored deformation. The KAM value of the E3 specimen showed a significant decrease, suggesting that dislocation recovery was further enhanced at higher pulsed currents. This trend is consistent with the reduction in rolling force and the increase in elongation at fracture, indicating that the release of stored intragranular deformation is an important microstructural factor contributing to the improved ductility of TA1 ultrathin strips under pulsed-current-assisted rolling.

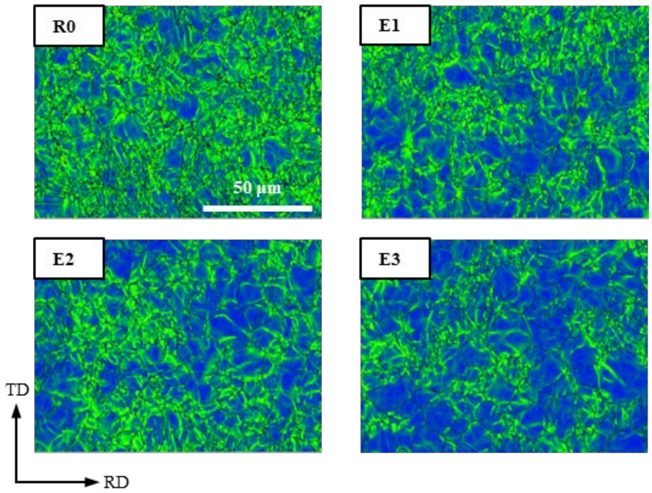

Fig.4 - Kernel average misorientation (KAM) diagram of room temperature rolled specimens and electrified rolled specimens

The evolution of deformed and substructured grains further supports the recovery mechanism described above. Figure 5 shows the distributions of recrystallized, substructured, and deformed grains in the room-temperature rolled specimen and the specimens rolled under different current amplitudes. The blue regions represent recrystallized grains with local misorientations of less than 1°, the yellow regions represent substructured grains with local misorientations between 1° and 7.5°, and the red regions represent deformed grains with local misorientations greater than 7.5°. As shown in Fig. 5, the degree of microstructural deformation in the electrically assisted rolled specimens differs significantly from that in the room-temperature rolled specimen.

With increasing pulsed current, the deformation microstructure of the pure titanium ultrathin strip gradually evolves toward a more substructured state. Compared with the room-temperature rolled specimen, the fractions of deformed grains in the E1, E2, and E3 specimens decrease by approximately 43.5%, 60.7%, and 82.0%, respectively, while the fractions of substructured grains increase to approximately 1.53, 1.71, and 1.94 times that of the room-temperature rolled specimen, respectively, showing a continuously enhanced tendency toward substructure formation with increasing current. These results indicate that, under pulsed-current assistance, highly distorted deformed grains progressively undergo dislocation rearrangement, leading to the formation of subgrain/substructure regions characterized by low-angle misorientations and dislocation walls, thereby promoting the transition of the material from a strongly work-hardened state toward a recovered state.

Meanwhile, none of the specimens exhibits pronounced recrystallization characteristics, indicating that the microstructural softening under the present conditions mainly originates from dislocation rearrangement and dynamic recovery rather than from the extensive formation of recrystallized grains. Combined with the variations in KAM, GND density, and microstructural volume fractions, the pure titanium ultrathin strip can be considered to undergo a continuous evolution process of “highly distorted deformation structure → dislocation rearrangement → substructure formation → enhanced recovery” with increasing pulsed current, thereby reducing local strain concentration and improving the subsequent plastic deformation capability.

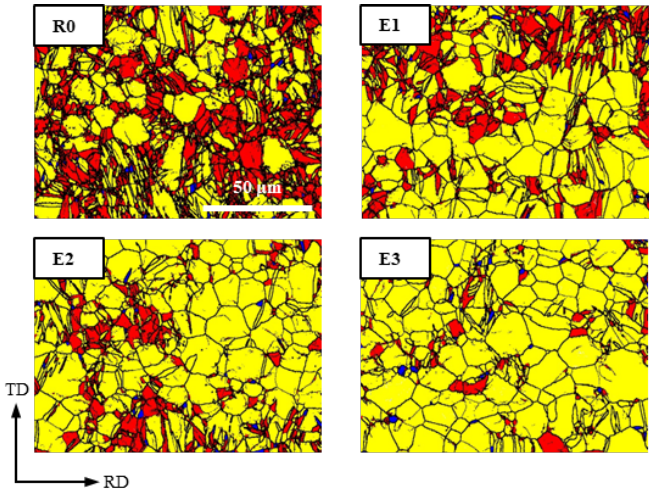

Fig.5 - Recrystallization distribution diagrams of conventional rolled specimen and electrified rolled specimens under different current magnitudes

CONCLUSION

Pulsed-current-assisted rolling experiments were conducted on TA1 commercially pure titanium ultrathin strips using a twelve-high precision rolling mill. The main conclusions are as follows:

(1) Pulsed current can effectively reduce the rolling deformation resistance of TA1 ultrathin strips and provide a larger processing margin for increasing the allowable single-pass reduction

(2) Pulsed current can reduce the degree of work hardening in rolled TA1 ultrathin strips, leading to a moderate decrease in strength and an increase in elongation, thereby improving the plastic deformation capability and subsequent formability of the material

(3) Pulsed current facilitates dislocation migration, rearrangement, and partial annihilation, promoting the evolution of the deformed microstructure toward a substructured and recovered state. The resulting reduction in intragranular distortion and local strain concentration is an important microstructural mechanism responsible for the enhanced ductility.

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