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Effect of Pulse Current on the Tensile Deformation of SUS304 Stainless Steel

Xifeng Li, Shen Wang, Shuangjun Zhao, Wei Ding, Jun Chen, and Guohong Wu

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The effect of pulse current on the mechanical properties of SUS304 metastable austenitic stainless steel was studied by tension test with and without air-cooling under different current densities. The microstructural variations at different conditions were also studied by SEM, TEM, and Feritscope. A negative effect on the plasticity was observed when current pulse was applied without air-cooling. But when Joule heating resulting from current pulse was excluded by air-cooling, the elongation of SUS304 stainless steel was increased to 72.4% at a current density of 2.95 A/mm^2, which is 23.3% higher than that tested without pulse current at room temperature. Pulse current can decrease the dislocation density and dislocation pile-ups. Furthermore, EP effect from pulse current can accelerate martensitic transformation and enhance TRIP effect. The mechanism of current-induced martensitic transformation was discussed from Gibbs free energy change.

Keywords dislocation, electroplastic effect, Gibbs free energy, SUS304 stainless steel, TRIP effect

1. Introduction

Over the last decades, electrically assisted forming (EAF) technology, in which electrical current is applied during deformation processes, has been proven to increase the workability of metals. It has been reported that electrically assisted deformation can reduce flow stress (Ref 1), increase the elongation (Ref 2), and decrease required deformation energy (Ref 3). Besides, EAF has been used in various forming processes such as eliminating springback in strip rolling (Ref 4), reducing the formability force in bending (Ref 5), and relieving residual stress during embossing process (Ref 6).

The difference between EAF and hot-working process is that pulse current can generate joule heating effect and electroplastic (EP) effect. EP effect is a nonthermal effect between the dislocations and drift electrons, which can increase the mobility of dislocations (Ref 7). The drift electrons help the dislocation to overcome the resistance from obstacles and lattices, thereby resulting in the deformation loading drop (Ref 8). Tang et al. (Ref 9) found that drawing stress was decreased to about 50% compared with conventional wire-drawing process. Moreover, the plasticity and surface quality of stainless steel wire were improved. Salandro et al. (Ref 5) proposed that the formability was significantly improved and the sample could be completely formed without failure during electrically assisted compression. However, EP effect has not been observed by all researchers. Recently, tension Kolsky bar experiments on 304SS and Ti-6Al-4V were conducted by Kinsey et al. (Ref 10). Their results illustrated that an EP effect did not exist up to 180 A/mm^2. Similarly, Magargee et al. (Ref 11) found that EP effect disappeared and flow stress was not reduced when tension specimens were air-cooled to room temperature. Thus, it is still unclear that flow stress reduction and elongation increase are caused by EP effect or rather by joule heating effect.

In recent years, many studies have focused on the effect of electric current on solid-state phase transformation in metals. Conrad et al. (Ref 12) believed that electric current helps to accelerate solid state phase transformation in metals and alloys in some cases. The results were influenced by many factors, such as composition, prior thermal treatment, density, and frequency of electric current. The cold-drawing test of stainless steel wire indicated that plenty of ferromagnetic phases are formed without current. However, the formation of ferromagnetic phases was diminished with pulse current (Ref 9). Actually, the influence of pulse current on phase transformation is still unclear. Further studies on the influence of pulse current on martensitic transformation are very necessary.

In this paper, the effect of pulse current on mechanical response of SUS304 metastable austenitic stainless steel was investigated. In order to distinguish EP effect from joule heating effect, three group tension tests were performed. The microstructural variations under different tensile conditions were observed by SEM and TEM. The effect of pulse current on martensitic transformation and transformation-induced plasticity (TRIP) effect was also discussed.

2. Experiment Methods

Uniaxial tension tests were performed on SUS304 metastable austenitic stainless steel sheet with a thickness of 1 mm, which chemical composition is listed in Table 1. Tension specimens were wire-cut with a gauge length of 25 mm and a gauge width of 6 mm. A SANS tensile machine was used to perform these experiments. A dc pulse power

Xifeng Li, Shen Wang, Shuangjun Zhao, Wei Ding, and **Jun Chen**, Department of Plasticity Technology, Shanghai Jiao Tong University, Shanghai 200030, China; and **Guohong Wu**, Dongguan Hengli Die and Mold Technological Industry Development Company Ltd., Dongguan 523460, China. Contact e-mail: jun_chen@sjtu.edu.cn.

Table 1 Chemical composition of SUS304 stainless steel sheet investigated (mass percent)

C	Si	Mn	P	S	Ni	Cr	Al	Fe
0.07	0.47	1.94	0.028	0.001	8.29	16.59	1.05	Balance

supply (TSGZ-2.0KVA capacitor banks) with a maximum dc voltage output of 400 V and a maximum dc current output of 300 A was used during electrically assisted tension.

Tension tests were divided into three groups: room temperature tension without current, EP tension, and EP tension with air-cooling. Two ends of samples were connected with the current source during EP tension, and the initial tensile strain rate was 5×10^{-3} s^{-1}. The temperature increase was measured by FLIR thermal camera. By blowing a stream of air from an air blower across the surface of tension specimens, the temperature due to Joule heating was reduced. The effective current during EP tension test could be recorded from the oscilloscope connected with power supply. The effective current density could be calculated:

$$C_d = I_0/A_0, \quad \text{(Eq 1)}$$

where C_d is an effective current density, I_0 is an effective current, and A_0 is an initial sectional area of tension specimen. The fracture surface of typical samples after tensile tests was observed by JSM-7600 SEM.

The dislocation density and martensite content are affected by strain, temperature, and current density. To eliminate strain influence and accurately compare dislocation density and martensite content changes under different conditions, all the specimens were stretched to the same elongation of 30%. After tension test, the stretched specimens were ground to a thickness of about 50 μm using increasingly finer grades of grit paper. Subsequently, the samples were thinned to perforation by twin-jet electro-polishing apparatus in a solution of 15 mL $HClO_4$ and 285 mL C_2H_5OH at 60 V and −30 °C. The tests were carried out by a JEM2100-type TEM with an accelerated voltage of 200 kV.

Moreover, to analyze the effect of temperature increase and pulse current on martensitic transformation, martensite volume fraction near fracture surface of the tensile specimens was measured by FMP30 Feritscope. In order to obtain the accurate data, this device was calibrated with standard samples. Parallel tests were performed three times, and the average value of three experiments was recorded.

3. Results

As shown in Fig. 1, when pulse current is applied, flow stress dramatically decreases with increasing current density. Compared with a maximum true stress of almost 1200 MPa without current, flow stress sharply decreases to about 400 MPa at a current density of 11.51 A/mm^2.

The maximum temperature at different current densities can be seen in Fig. 2. The maximum temperature at 11.51 A/mm^2 reaches 351.9 °C. It is noticeable that the stress reduction strongly correlates with temperature increase resulting from Joule heating. Thus, it is unclear that the stress reduction is due to EP effect or caused by temperature increase. The additional

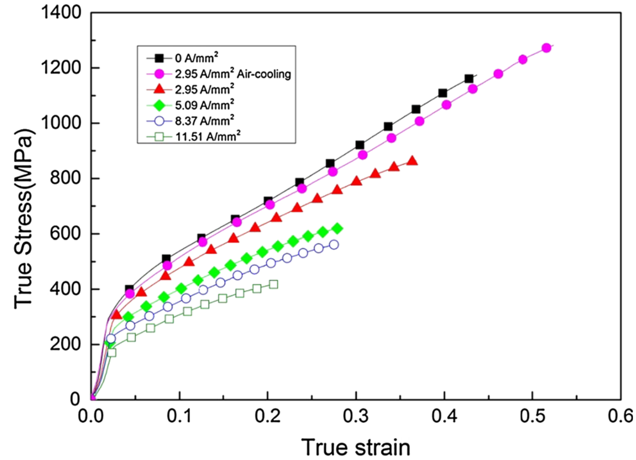

Fig. 1 True stress-strain curves of tensile samples at different current densities

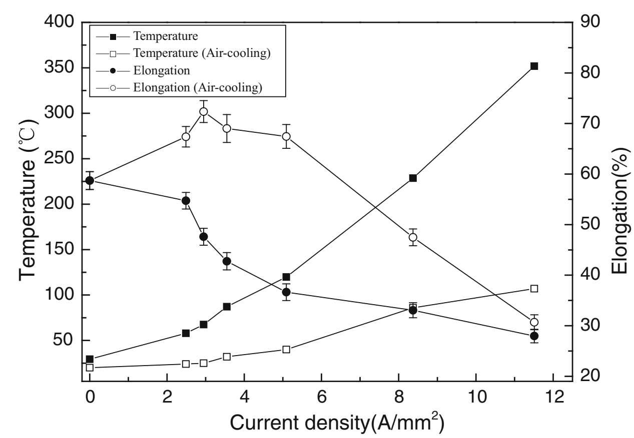

Fig. 2 Maximum temperature and elongation at different current densities

experiments were conducted during EP tension tests, in which Joule heating effect was decoupled from EP effect by air-cooling. The specimen at 2.95 A/mm^2 with air-cooling was chosen to compare with conventional and no air-cooling specimens. The maximum temperature during tension at 2.95A/mm^2 was 57.9 °C. When air-cooling was applied, the maximum temperature was decreased to room temperature of 20 °C, at which Joule heating effect could be neglected. The flow stress curves of the tested specimens with and without pulse current almost overlap each other in the initial elastic deformation stage. This indicates that pulse current little affects elastic modulus of stainless steel. Similar phenomenon was found in electroplastic tension of 316L stainless steel under different current density and temperature (Ref 13). During the plastic deformation, the flow stress with pulse current and air-cooling obviously reduces in comparison with no current. Thus, EP effect exists and helps to decrease the flow stress.

In general, the tensile strength decreases and the elongation increases with temperature increase. Pulse current can increase the elongation and improve the deformation ability. However, Fig. 2 shows that the elongation decreases with increasing current density, which is very different from previous results from many researchers (Ref 1, 2, 10, 14). When a current

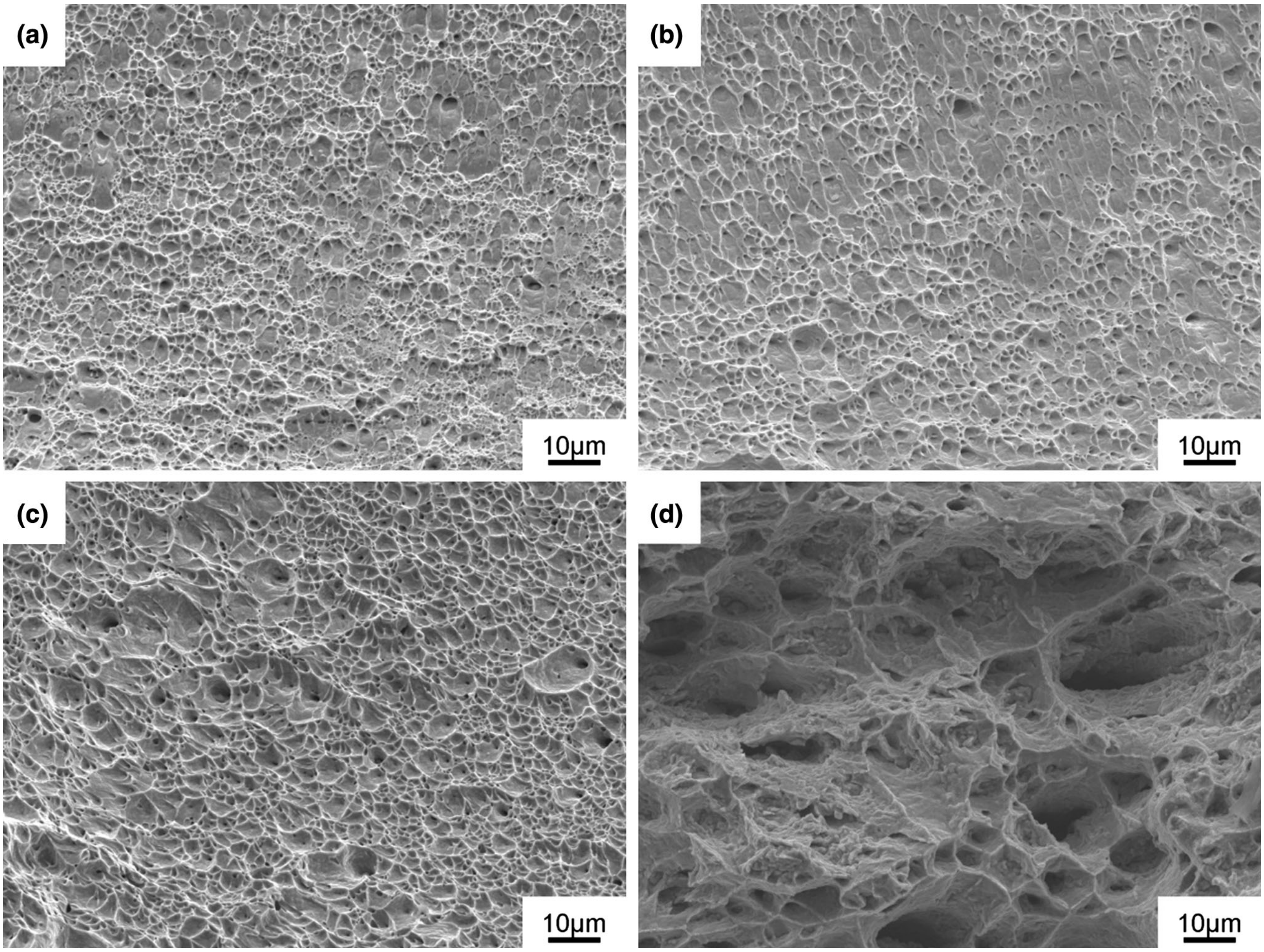

Fig. 3 SEM fracture surfaces tested at different conditions: (a) at room temperature, (b) at 2.95 A/mm^2 without air-cooling, (c) at 2.95 A/mm^2 with air-cooling, (d) at 11.51 A/mm^2

density increases to 11.51 A/mm^2, the elongation decreases to 28%, which is far smaller than the conventional elongation of 58.7%. In EP tension tests with air-cooling, an opposite result is obtained. The elongation increases to 72.4% at 2.95 A/mm^2, which is 23.3% higher than that at room temperature without current, and 52.1% higher than that at 2.95 A/mm^2 without air-cooling. In order to avoid experiment error, more air-cooling tension tests at various current densities were performed. The temperature increase was also compared with no air-cooling conditions. The elongation increases with current density when the current density is less than 2.95 A/mm^2. When current density is relatively small, Joule heating can be totally eliminated and EP effect was separated from thermal effect by air-cooling. On further increasing current density, Joule heating cannot be entirely eliminated by air-cooling and the elongation declines. But the elongation is still larger than that tested without current when current density is less than 5.09 A/mm^2. From the experiment results above, it can be concluded that Joule heating plays a dominant role in the elongation change of SUS304 stainless steel during electrically assisted tension.

Figure 3 shows the fracture surface tested under different conditions. Many small dimples are observed on fracture surface in Fig. 3(a), which indicates typical ductile fracture characteristics at room temperature. The dimples become less and shallower and even disappear in some area at 2.95 A/mm^2 (Fig. 3b). Compared with dimples shown in Fig. 3(a) and (b), the dimples in Fig. 3(c) become wider and deeper, which reveals that the specimens undergoing more significant plastic deformation before fracture and exhibits larger plasticity. Fig. 3(d) shows irregular fracture surface at 11.51 A/mm^2. Void-defect occurs and brittle fracture happens in some area. These fracture surfaces coincide with elongation variation shown in Fig. 2.

Figure 4 reveals TEM micrographs of samples stretched to an elongation of 30% at different conditions. As shown in Fig. 4(a) and (b), many lath martensites and dislocation pile-ups are found at room temperature. Martensite is a strain-induced phase during the plastic deformation. TRIP effect can increase the ductility and delay necking and cracking because the retained austenite transforms into martensite. SUS304 stainless steel is a typical TRIP steel, and strain-induced martensite is helpful to improve the ductility, which results in high work hardening rate and good ductility. In Fig. 4(c) and (d), a mass of martensite is still observed at 2.95 A/mm^2 with air-cooling. However, the dislocation tangles and dislocation density are significantly reduced. Compared with martensitic distribution in Fig. 4(a), (c), and (e) shows a smaller amount of lath martensite. When a current density reaches to 8.37 A/mm^2, the martensite almost disappears and the dislocation density decreases (Fig. 4f), in which the TRIP effect is totally restricted.

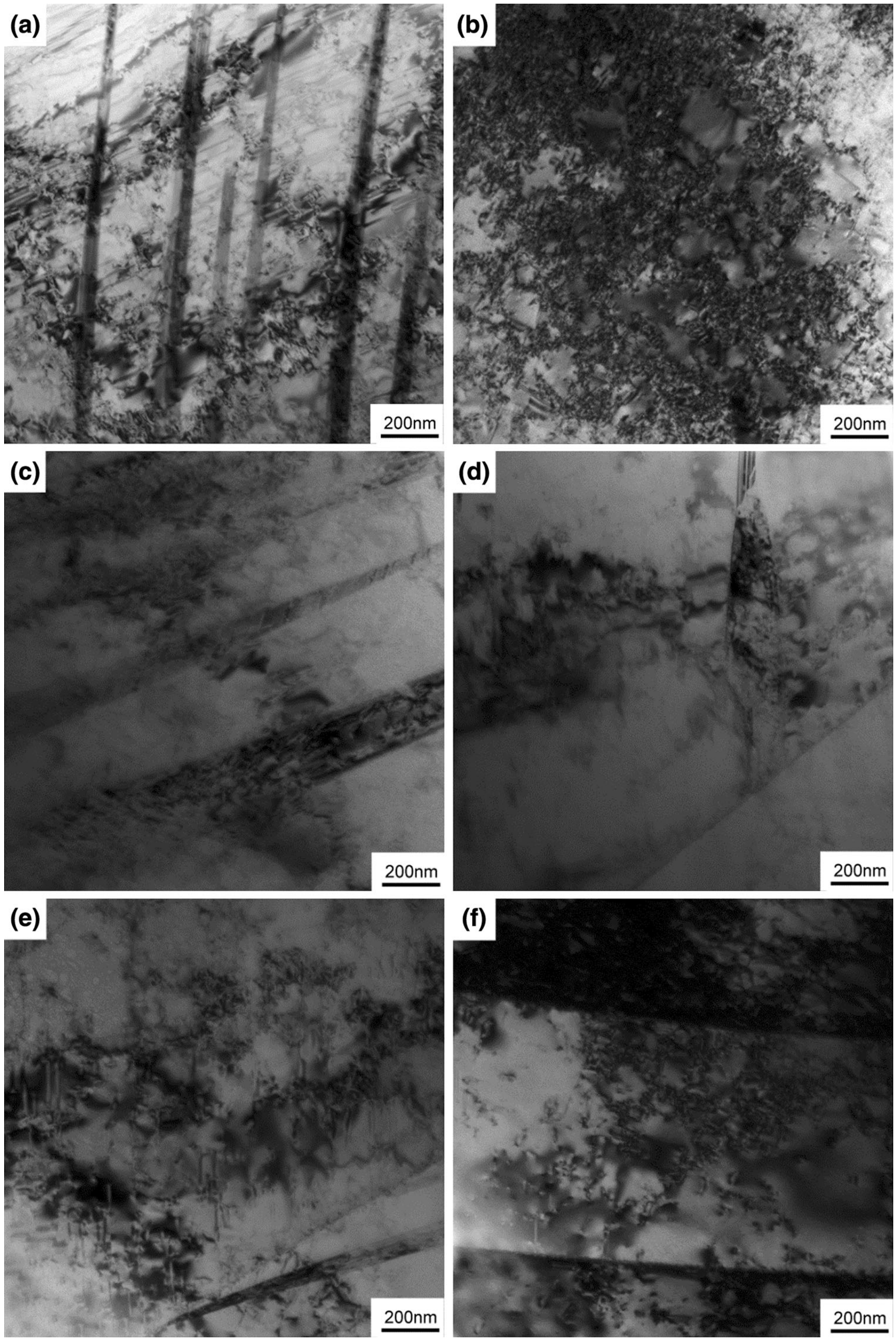

Fig. 4 TEM micrographs of samples stretched to an elongation of 30% at different conditions: (a) and (b) at room temperature, (c) and (d) at 2.95 A/mm^2 with air-cooling, (e) at 2.95 A/mm^2 without air-cooling, (f) at 8.37 A/mm^2

The dislocation glides by external force driving during plastic deformation. The dislocation pile-ups are formed when the dislocations bump against the obstacles. Then, the subsequent deformation becomes harder and dislocation density increases. When pulse current is applied, the drift electrons help the dislocations overcome the resistance from obstacles and lattice resistance. Thereby, the required force to move the dislocations is reduced and the dislocation density and pile-ups decrease. As current density increases, the force of the drift electrons becomes larger, which results in a drop of required deformation energy and flow stress. On the other hand, the dislocation density reduction decreases the crystal defects and delays the generation of crack, which contributes to the elongation improvement. This is verified by the elongation

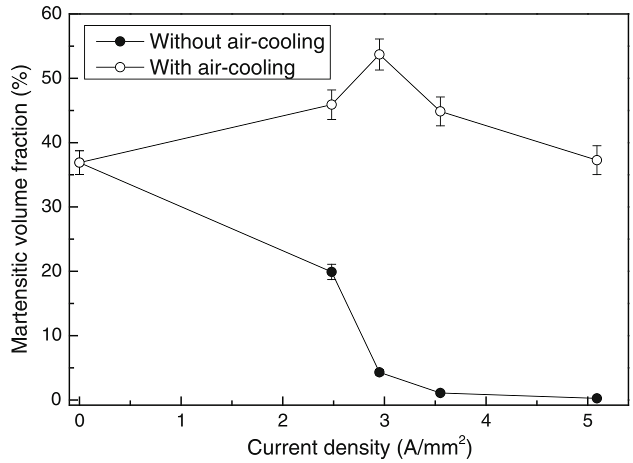

Fig. 5 Martensitic volume fraction near fracture surface of tensile specimens at different conditions

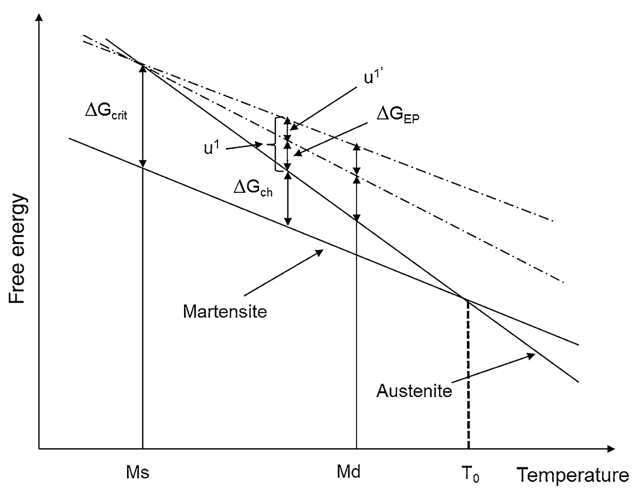

Fig. 6 The relationship between free energy and temperature during martensitic transformation

improvement at 2.95 A/mm^2 with air-cooling in comparison with room temperature tension without current. However, compared with the influence of TRIP effect on the elongation of SUS304 stainless steel, the dislocation density is just a minor factor. Therefore, it can be seen that increasing current density decreases the elongation in Fig. 1 and 2, where the TRIP effect is restrained in different extent.

As shown in Fig. 5, a martensitic volume fraction dramatically near fracture surface of tensile specimens decreases with increasing current density without air-cooling, which is 36.9% at room temperature. And it sharply decreases to 0.26% at 5.09 A/mm^2. This means that almost no martensite was transformed during EP tension. In other words, TRIP effect decreases with increasing current density. However, the martensitic volume fraction increases to 53.7% at 2.95 A/mm^2 with air-cooling. Although a small amount of Joule heating exists, martensitic volume fraction at 5.09 A/mm^2 still reaches to 41.3%. Therefore, EP effect can promote martensitic transformation and enhance TRIP effect. The elongation increases when Joule heating is seriously restricted by air-cooling.

4. Discussion

Chemical Gibbs free energy difference between austenite and martensite provides the driving force of martensitic transformation in metastable austenitic stainless steel (Ref 15). The mechanism of martensitic transformation under EAF deformation can be explained as follows. As shown in Fig. 6, the chemical free energy of austenite and martensite is equal at T_0, and they are thermodynamic equilibrium. When there is no additional energy available, the minimum driving force required for inducing martensitic transformation is the minimum free energy ΔG_{crit}, which is equal to the chemical free energy difference ΔG_{ch} between retained austenite and martensite at the martensite starting temperature M_s.

During plastic deformation, martensitic transformation can be triggered between M_s and the highest temperature of martensitic transformation M_d due to some additional energy. The internal strain energy u^1 is taken as a consequence of the dislocation pile-ups due to strong barriers such as grain boundaries during the plastic deformation (Ref 16, 17). The additional energy is totally provided by the internal strain energy u^1 without pulse current. Therefore, the required internal strain energy for strain-induced martensitic transformation can be described as

$$u^1 = \Delta G_{\mathrm{crit}} - \Delta G_{\mathrm{ch}}. \quad \text{(Eq 2)}$$

The driving force for phase transformation consists of three parts: chemical Gibbs free energy, internal strain energy, and current-induced Gibbs free energy. The current-induced Gibbs free energy ΔG_{EP} provides additional energies for martensitic transformation, which can be expressed by (Ref 18):

$$\Delta G_{EP} = -N\Delta W_{EP}, \quad \text{(Eq 3)}$$

where N is a number of martensitic nucleus, ΔW_{EP} is an energy change due to the distribution change of the current in the formation of a martensitic nucleus, which is given by (Ref 18, 19):

$$\Delta W_{EP} = \mu g \xi(\sigma_1, \sigma_2)\Delta V C_d^2, \quad \text{(Eq 4)}$$

where μ is a magnetic susceptibility; g is a geometric factor; ΔV is a volume of a nucleus, and C_d is a effective current density. $\xi(\sigma_1, \sigma_2)$ is a factor that depends on the electrical properties of nucleus and medium, where σ_1 is the conductivity of the martensitic phase and $\sigma_2$is the conductivity of austenitic phase. The sign of ΔW_{EP} is determined only by the sign of $\xi(\sigma_1, \sigma_2)$, and $\xi(\sigma_1, \sigma_2)$ is expressed by (Ref 18, 19)

$$\xi(\sigma_1, \sigma_2) = \frac{\sigma_2 - \sigma_1}{\sigma_1 + 2\sigma_2}. \quad \text{(Eq 5)}$$

During the temperature region of martensitic transformation, $\sigma_1 > \sigma_2$ and the electrical conductivity in 304 stainless steel may increase by about 7.5% at 20% transformation to martensite (Ref 20, 21), this gives $\xi(\sigma_1, \sigma_2) < 0$ and then $\Delta G_{EP} > 0$.

With the addition of ΔG_{EP}, the total Gibbs free energy is increased and the driving force of martensitic transformation is also significantly increased. In this case, the required internal strain energy for strain-induced martensitic transformation can be obtained by

$$u^{1'} = \Delta G_{\mathrm{crit}} - \Delta G_{\mathrm{ch}} - \Delta G_{EP}. \quad \text{(Eq 6)}$$

According to Eq 2 and 6, the required internal strain energy $u^{1'}$ is less than u^1 at the same temperature due to $\Delta G_{EP} > 0$.

Therefore, the martensitic transformation becomes easier to take place with pulse current. The martensitic volume fraction increases when air-cooling is applied. However, the temperature increase resulting from Joule heating narrows the chemical Gibbs free energy difference between austenite and martensite. Therefore, more additional energy is required to induce martensitic transformation without air-cooling. Under this circumstance, Joule heating plays a leading role during martensitic transformation regardless of the existence of current-induced Gibbs free energy. Martensitic transformation cannot take place when the temperature is higher than M_d. Consequently, the martensite volume fraction decreases with increasing current density without air-cooling.

EP effect can accelerate martensitic transformation of SUS304 stainless steel when Joule heating is eliminated by air-cooling. The plasticity depends on two factors: TRIP effect and the dislocation movement. On one hand, pulse current promotes martensitic transformation and enhances the TRIP effect, which results in the plasticity improvement. On the other hand, the dislocation density reduction decreases the crystal defects and delays the generation of crack, which also leads to the elongation improvement. When a pulse current is applied without air-cooling, TRIP effect was severely restricted because of temperature increase. The dislocation density decrease fails to compensate for the restricted TRIP effect. Therefore, the elongation decreases with increasing current density.

5. Conclusions

EP tension tests with and without air-cooling on SUS304 metastable austenitic stainless steel were performed under different conditions. SEM, TEM observation, and martensite volume fraction measurement were applied. The following conclusions can be drawn:

1. The elongation of SUS304 stainless steel is increased to 72.4% at 2.95 A/mm^2 with air-cooling, 23.3% higher than that tested without pulse current. Pulse current can accelerate martensitic transformation and enhance TRIP effect when Joule heating is seriously eliminated by air-cooling.
2. When Joule heating from pulse current exists, the temperature increase plays a dominant role in restricting martensitic transformation. The elongation decreases with increasing current density without air-cooling.
3. Pulse current can decrease the dislocation density and pile-ups and improve the dislocation movement, which results in plasticity increase and flow stress decrease.

Acknowledgments

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