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Effect of pulse current on bending behavior of Ti6Al4V alloy

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Abstract

The tensile properties and bending behavior of Ti6Al4V alloy sheet with pulse current were studied. The current density greatly affects the tensile strength and elongation. With current density increasing, the flow stress greatly reduces and the elongation obviously increases. Actually, the effect of the pulse current on flow stress is more significant than that on the failure strain. The current pulse can obviously improve the bending properties of Ti6Al4V alloy. The bending cracks can be avoided with current pulse, which always appears with no current. The electroplastic effect mainly results from a comprehensive function of Joule heating and pure electroplastic effect. Among them, Joule heating effect perhaps plays a dominant factor.

Keywords: Ti6Al4V alloy; Bending behavior; Pulse current; Electroplastic effect

1. Introduction

Titanium alloys are a kind of advanced material with high specific strength, excellent corrosion resistance, good weldability and high-temperature performance, which have been widely applied in the fields of aerospace, chemical processing, marine and offshore, transportation and medicine, etc. (Leyens et al., 2003; Yang et al., 2011). However, titanium alloys are difficult to form due to high deformation resistance, low ductility, large anisotropy,
and high microstructural sensitivity to processing at room temperature, which results in the increase of production cost and period. Consequently, it is very important to develop an advanced forming technique which can improve the precision and quality of titanium parts.

One evolving alternative processing is electrically-assisted forming (EAF). In this process, a direct electrical current is used through the specimen being subjected to deformation, which leads to a decrease in flow stresses and microstructure refinement, as well as to improvements in the deformability, microhardness, and other mechanical properties of the material (Jones et al., 2013; Frolova et al., 2013). Yanagimoto et al. studied a continuous electric resistance heating-hot forming system for Ti6Al4V bar. This bar was successfully formed without fracture. Ross et al. (2009) investigated the use of electricity to assist in the bulk deformation of Ti6Al4V under tensile and compression loads. Their work fully demonstrated that an electrical current can be used to significantly improve the formability of Ti6Al4V and that these improvements far exceed that which can be explained by resistive heating. Salandro et al. (2010) examined air bending of 304 stainless steel sheet. Using an analytical approach, a model of the forming load was developed for conventional bending and electrically-assisted bending, which combined both mechanical and thermal effects. The model can approximately predict the forming load during the process. However, the modelling approach only considered a single bulk temperature to characterize the thermal effects of a large component containing large thermal gradients (Jones et al., 2013; Salandro et al., 2010). This present work investigated the tensile properties and bending behaviour of Ti6Al4V alloy sheet with pulse current.

2. Experimental procedure

Ti6Al4V titanium alloy sheets (0.5 mm) were selected as the experimental materials. The tensile samples were wire cut from these sheets, which gauge size was 25mm in length and 6mm in width. Pulse current flowed tensile samples by TSGZ-2.0KVA capacitor banks under ambient condition. The amplitude and the frequency of the pulse current can be adjusted through the capacitor banks. The frequency and the duration during a period ($T$) of the pulse current is 120 Hz and 60 $\mu$s ($t_1$), respectively. The peak current magnitude ($I_m$) was detected by a digital storage oscilloscope. Then the root mean square density was calculated by Eq. (1), where $A$ is the cross-section area of the gauge in the tensile samples. The root mean square density ($I$) from 0A/mm$^2$ to 12.0 A/mm$^2$ was applied.

$$I = \frac{I_m \times \sqrt{t_1}}{2T}. \quad (1)$$

The tensile tests were divided into two groups: room-temperature tension without current, electroplastic tension. The SANS test machine was chosen to perform electroplastic tensile tests, and the two ends of samples were connected with the current source during the electroplastic tension, and the initial tensile strain rate was $5 \times 10^{-3}$ s$^{-1}$, as shown in Fig. 1. The temperature increase during electroplastic tension was measured and recorded by FLIR-A651 infrared camera, which lens focuses on the middle zone of the gauge. The temperature data is processed by the BM_IR software.

Electroplastic bending tests were also performed on SANS test machine. Electroplastic bending tool were designed and machined, as shown in Fig. 2. The bending radius is 1mm. Cu electrodes were embedded in punch and die, which were connected to the current source. The bakelite was used for insulation between bending tool and compression tester. The bent blank is 50 × 50 mm, and the bending angle is 90°. All tensile and bending tests were repeated at least three times in order to ensure the repeatability and reproducibility of experimental results.
3. Results and discussion

Fig. 3 shows the true stress-stain curves of Ti6Al4V alloy sheet at different conditions. With current density increasing, the flow stress greatly reduces and the failure strain obviously increases. Actually, the effect of the pulse current on flow stress is more significant than that on the failure strain. The tensile strength decreases from 1100 MPa at room temperature to 743 MPa at 4.2 A/mm², however, the failure strain only increases from 0.113 to 0.118. Fig. 4 indicates the elongation of the Ti6Al4V alloy sheet is significantly improved with pulse current. When the current density increases to 12.0 A/mm², the elongation increases to 64%. Compared with 12% at room temperature, the elongation improves by above 4 times. However, when the current density is 4.2 A/mm², the elongation fewly changes in contrast with that without current. Andrawes et al. (2007) proposed a current density threshold value for electroplastic effect. Actually, this result is not consistent with his finding. There seems no current density threshold value of Ti6Al4V alloy for electroplastic effect. Because when the current density is 4.2 A/mm², the flow stress can be greatly deceases.

Fig. 5 shows the temperature distribution at 12.0 A/mm² measured by infrared camera. The highest temperature can reach to 620.4 °C. Therefore, the Joule heating effect is significant and plays a main role in electroplastic effect. Magargee et al. (2013) conducted uniaxial tensile tests on thin CP titanium sheets subjected to electrically
assisted deformation. A maximum temperature is 434.6 °C with a current density of 16 A/mm². When the specimens were air-cooled to approach room temperature, stress decrease was not observed. Kinsey et al. (2013) performed a dc charged Kolsky bar experiment for 304 stainless steel and Ti6Al4V with high tensile rates. The electroplastic effect was not observed and flow stress reduction was strongly temperature dependent. This result seems to accord with their conclusion. Actually, it is still controversial whether the flow stress decrease upon the passage of electric current resulted from a non-thermal electroplastic effect or some amount of thermal softening. The role and percentage of Joule heating among the electroplastic effect alone will be studied in the future.

![Fig.3. True stress-strain curves of Ti6Al4V alloy sheet at different conditions.](image1)

![Fig.4. Tensile specimens at different conditions.](image2)

![Fig.5. Measured temperature distribution at 12.0 A/mm².](image3)
Fig. 6 reveals the bent specimens with no current and pulse current. It is obvious that the specimens easily crack without current. On the contrary, the specimens can be successfully bent without macroscopic cracks when the pulse current is employed, which reveals the current can improve the formability of Ti6Al4V alloy sheet and electroplastic effect obviously exists. Otherwise, the next work is the temperature measurement during the bending tests and microscopic crack observation on the bent samples.

![Fig. 6. Bent specimens with no current and pulse current.](image)

The bending displace-load curves of Ti6Al4V alloy sheet at different conditions are shown in Fig. 7. With current density increasing, the forming load obviously decreases. When the displacement is 4mm, the load without current and at 5.57 A/mm² is 2.19kN and 1.79 kN, respectively. And the load decreases by 18.3%. Therefore, electroplastic effect can greatly decrease the forming force. Actually, it is difficult to bend titanium alloy components at room temperature without thermal- or electrical-assisted forming. However, it is a perspective that electroplastic effect can apply in the bent industry of titanium alloy sheet as shown in Fig. 8.

![Fig. 7. Displace-load curves of Ti6Al4V alloy sheet at different conditions.](image)
4. Conclusion

The tensile elongation and bending formability of Ti6Al4V alloy sheet with pulse current can be obviously improved. It is mainly resulted from Joule heating effect. The highest temperature at 12.0 A/mm² can reach to 620.4 °C. There seems no current density threshold value of Ti6Al4V alloy for electroplastic effect. The effect of the pulse current on flow stress is more significant than that on the failure strain. The bending crack can be avoided with pulse current, which always appears without current. It is a perspective that electroplastic effect can apply in the bent industry of titanium alloy sheet.

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References

Leyens, C., Peters M., 2003. Titanium and Titanium alloys. Weinheim: Wiley-VCH.

Yang, H., Fan, X.G., Sun, Z.C., Guo, L.G., Zhan, M., 2011. Recent development in plastic forming technology of titanium alloys. Science China: Technological Sciences, 54(2):490-501.

Jones, J.J., Mears, L., 2013. Thermal response modeling of sheet metals in uniaxial tension during electrically-assisted forming. Journal of Manufacturing Science and Engineering, 135(021011):1-11.

Frolova, A.V., Stolyarov, V.V., 2013. Effect of pulse current on deformability, structure, and properties of NbTi alloy superconductor. Journal of Machinery Manufacture and Reliability, 42(4): 325-330.

Yanagimoto, J., Izumi, R., 2009. Continuous electric resistance heating-Hot forming system for high-alloy metals with poor workability. Journal of Materials Processing Technology, 209(6):3060-3068.

Ross, C.D., Kronenberger, T.J., Roth, J.T., 2009. Effect of dc on the formability of Ti-6Al-4V. Journal of Engineering Materials and Technology, 131(031004):1-11.

Salandro, W.A., Bunget, C., Mears, L., 2010. Modeling and quantification of the electroplastic effect when bending stainless steel sheet metal. ASME International Manufacturing Science and Engineering Conference, Erie, PA, MSEC2010-34043:581-590.

Andrewes, J. S., Kronenberger, T. J., Perkins, T. A., Roth, J. T., Warley, R. L., 2007. Effects of DC Current on the Mechanical Behavior of AlMgSiCu. Materials and Manufacturing Processes, 22 (2007) 91-101.

Magargee J., Morestin, F., Cao, J., 2013. Characterization of flow stress for commercially pure titanium subjected to electrically assisted deformation. ASME Journal of Engineering Materials and Technologies, 135(4):041003-041003-10.

Kinsey, B.L., Cullen G., Jordan, A., Mates, S., 2013. Investigation of electroplastic effect at high deformation rates for 304SS and Ti-6Al-4V. CIRP Annals-Manufacturing technology, 62(1):279-282.