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Effects of deformation rate on ductility of Ti-6Al-4V material

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Abstract

To determine the velocity field in which the Ti-6Al-4V titanium alloy sheet was sensitive to the strain rate, the formability at different strain rates were tested using a ring sample in the electromagnetic ring expansion experiment. For the test of titanium alloy, an aluminum alloy loop was used as a driver ring due to improve energy efficiency. The expansion velocity and strain rate of titanium ring were predicted by a numerical simulation method which had been verified by experimental data obtained with a high speed camera. The uniform strain was defined as the ratio of the change and the one after expansion of the cross sectional area in this study. Since the fracture strain of a material was related to the aspect ratio (ratio of length to diameter) of samples, the uniform strain was chosen to characterize the ductility of the material. The results indicate that when the tensile speed of Ti-6Al-4V titanium alloy sample is 2 mm/min (quasi-static), the strain rate of deformation is 6.67×10^{-4} 1/s and its uniform strain (ε_u) reaches 0.102. Instead, the uniform strain is only 0.032 when the expanding speed of 46.7 m/s is faster than the quasi-static speed. However, the uniform strain increases proportionally with the increment of the strain rate, and exceeds the quasi-static uniform strain reaching 0.11 or more when the deformation speed is faster than 286 m/s, in which the strain rate exceeded 6935.6/s. Therefore, the deformation speed of 286 m/s or the strain rate of 6935.6 1/s could be considered as the threshold to improve the ductility of Ti-6Al-4V titanium alloy.

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Keywords: Electromagnetic pulse forming; Ring expansion; High velocity forming; Ductility; Ti-6Al-4V titanium alloy.

1. Induction

The ductility of materials at high speed forming is drawing more and more attention due to the widespread application of the high speed forming process such as electromagnetic forming and explosive forming. The earliest report in this field (Wood, 1967) showed that the ductility of dynamically loaded tensile specimens generally

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increased. Electromagnetic forming has provided as an effective method for forming low plasticity and difficult forming materials such as aluminum alloy.

At high speed forming, there are two critical points of the strain rate sensitive velocity, so the deformation velocity of material is divided into three regions. Below the first critical point of velocity is the quasi-static field, such as the speed of traditional presses when processing, and the strain rate sensitivity has nothing to do with the ductility of material. When the deformation velocity is higher than the second critical value, the material necks soon and fractures. When the strain lies between the first and second critical velocity (the so-called von Karman velocity), which is related to the plastic wave velocity in the material, and the ductility of the material can be improved (Meyers, 1994). An improvement in formability in pulsed forming was reported where the pulsed forming results were compared with that with low speed dynamic deformation and quasi static forming conditions: the increase of formability in pulsed forming was much higher than in low speed dynamic forming (Dariani et al., 2009).

The increase in formability observed at high-speed forming has been attributed to constitutive behaviour, inertial effect, and die impact effect. As analysis of tensile samples (Hu and Daehn, 1996) and experimental results with rapidly expanding rings (Altynova et al., 1996) shows that inertial effect could account for an approximate doubling in the instability strain.

In this paper, the electromagnetic ring expansions of Ti-6Al-4V rings by using the aluminum driver rings were conducted with different discharge voltages to study the effects of the deformation rate on the ductility of Ti-6Al-4V material. The deformation rate or strain rate was predicted by a proved numerical simulation method and their relationships with the ductility of Ti-6Al-4V were drawn out. The mechanism of the deformation rate or stain rate affecting the ductility of Ti-6Al-4V was analysed in details.

2. Experiment and numerical simulation

2.1. Material and dimensions of sample

The material used in this study was Ti-6Al-4V titanium alloy sheet with 1mm thick. The rolled sheet was heated and maintained at 820ºC for 30 minutes, and then cooled in the air. The phase transition point of the material determined by metallographic observation, is 975-976 ºC. The chemical composition of Ti-6Al-4V is provided in Table 1 and the mechanical properties are listed in Table 2.

Table 1. Chemical composition of the titanium alloy Ti-6Al-4V.

Element	Ti	Al	V	Fe	C	N	H	O	Other
Weight (%)	Base	6.07	3.99	0.04	0.01	0.01	0.015	0.12	Total<0.40 (Each<0.10)

Table 2. Properties of the Ti-6Al-4V at room temperature.

Material	Yield strength (MPa)	Ultimate tensile strength (MPa)	Elongation (%)	Thickness (mm)	Resistance (μΩ·cm)
Ti-6Al-4V	1000	1040	11.52	1	169.3

The Ti-6Al-4V titanium ring samples were cut by electrical discharge wire-cutting according to the dimension of the solenoid coil, as shown in Fig. 1. Due to the high resistivity of titanium, an aluminum loop with 10mm in height was used as a driver ring.

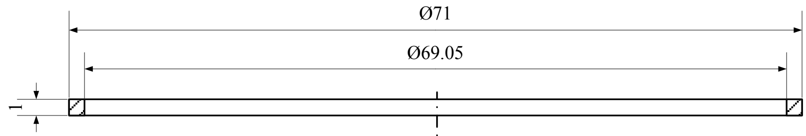

Fig. 1. Dimension of the titanium ring.

2.2. Electromagnetic expansion coil

A solenoid coil was used in electromagnetic expansion experiment, the effective size of the wire part was Ø28mm in the inner diameter, Ø56mm in the outer diameter and 24mm in height. It was tightly wound with six layers and 30 turns using glass envelope with 2 × 4mm in cross-sectional dimensions. The outer layer was reinforced with epoxy resin and the outer dimension was Ø65mm, as shown in Fig.2. Besides, A 10×1mm nylon ring was used to ensure uniformity in the gap between the sample ring and the coil.

2.3. Electromagnetic expansion ring tooling

In the electromagnetic ring expansion, the coil was clamped by the upper and lower plate using nuts. In order to facilitate collecting the fragments of the ring samples and avoid the high-speed crash, the coil was surrounded with a layer of foam. The current of discharge circuit and deformation displacement of sample ring during the expansion are essential to calculate the expanding velocity of sample. The sample ring was placed in the middle of the effective height of the solenoid coil and the high resolution images of the sample ring at difference times were recorded with high-speed cameras FASTCAM SA-X, as shown in Fig. 3. The deformation process of the specimen in one set of experiments was tested using the resolution and frame rate at 512x288@50,000 fps. The camera was calibrated to make the lens flush with the expansion coil before the test, so that the information collected in the picture was on one 2D plane. According to the obtained images, the displacement of the Ti ring varying with time could be obtained by information processing using FASTCAM viewer 3.0 software (pixel analysis). The output voltage signal of an oscilloscope was used to trigger the high speed cameras during testing.

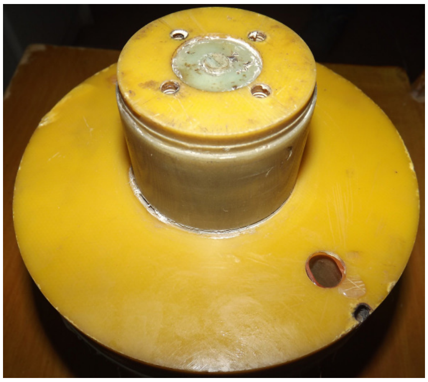

Fig. 2. Electromagnetic expansion coil.

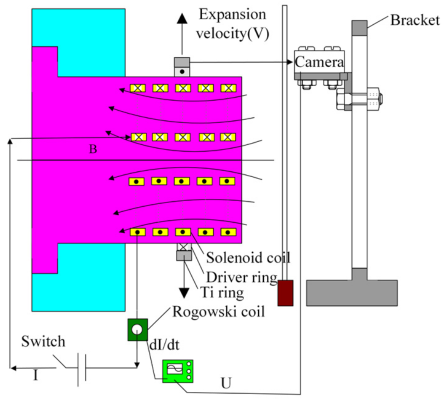

Fig. 3. Schematic of electromagnetic ring expansion.

2.4. Experimental process

First, a suitable placement of sample ring at the solenoid coil was determined using the trial and error method to ensure that the ring deformed uniformly during the electromagnetic expansion. Then, an electromagnetic expanding ring experiment was carried out on the aluminum ring with Ø67 mm in the inner diameter, Ø71 mm in outer diameter and cross-sectional dimensions of 2×2 mm.The discharge voltage was 6 kV and the capacitance was 80μf. The displacement and velocity varying with time of the aluminum ring, which were used to verify the reliability of the numerical analysis, were obtained by the high-speed camera during this experiment. The electromagnetic experiments of titanium rings using aluminum driver rings with different heights were per formed to determine the appropriate height of the driver ring. Finally, electromagnetic ring expansion experiments of titanium rings with 1×1 mm in the cross-sectional dimensions under different discharging voltages were carried out separately and the aluminum driver rings were used to improve energy efficiency. The capacitance of the electromagnetic forming device was 213 μf and kept unchanged, while the discharge voltage was changed to obtain different expanding speed. The effects of deformation rate on the formability of titanium were obtained by measuring the cross-sectional area and length of the recovered rings respectively and analysing the relationship between the uniform strain of material and the expanding speed.

3. Results

During the experiment, the capacitance was kept 213μf and the discharge voltage of 4.5, 5.0, 5.5, 6.0, 6.5, 7.0, and 7.5kV was adopted respectively. The recovery sample rings are shown in Fig. 4 after the electromagnetic expansion. Since the fracture strain is closely related to cross-sectional size of the sample, it cannot be used to characterize the ductility of material (Tamhane et al., 1996). Therefore, the uniform strain of the sample ring was used here and calculated as follows:

$$\varepsilon_u = \frac{A_0 - A}{A} \ , \qquad (1)$$

where A_0 is the original cross-sectional area of the specimen ring, A is the cross sectional area of the recovery sample ring. When measuring the cross-sectional area, the position away from necking was chosen to measure in order to avoid measurement errors. Besides, various positions were measured and then averaged.

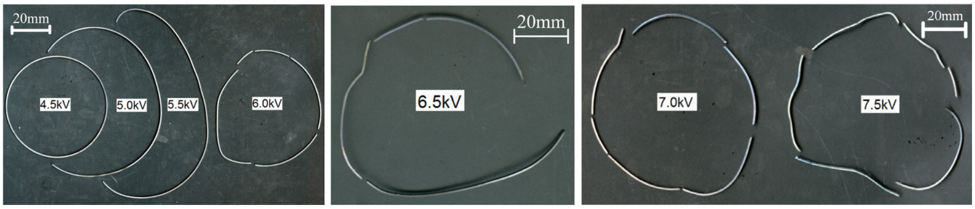

Fig.4. Titanium samples collected at different discharge voltage.

The deformation velocities and strain rates of the Ti-6Al-4V titanium rings during the electromagnetic ring expansion using 10×1 mm aluminum driver rings were calculated by a proved numerical simulation method. Fig. 5 shows the expansion velocity of the titanium ring varying with time at different discharge voltages. It can be found that the expansion velocity increases with the increment of the discharge voltage. The maximum expansion velocity of the Ti-6Al-4V titanium ring (V_{max}) is 335.1 m/s when the discharge voltage is 7.5 kV. Fig. 6 is the variation in the strain rate of the titanium ring with time at different discharge voltages, where it can be seen that the strain rate increases with the discharge voltage increasing. When the discharge voltage is 7.5 kV, the maximum strain rate ($\dot{\varepsilon}_{max}$) approaches 8686.09 1/s.

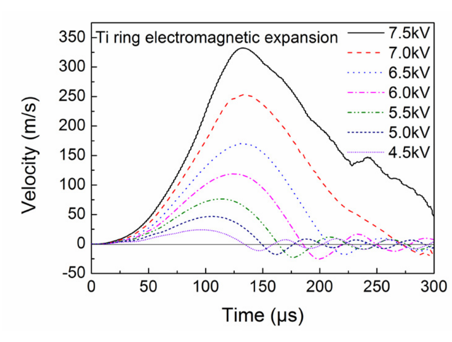

Fig. 5. Expansion velocity varying with time at different discharge voltages.

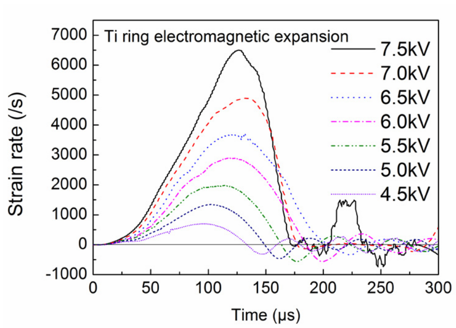

Fig. 6. Strain rate varying with time at different discharge voltages.

Effects of the deformation velocity and strain rate on the uniform strain of titanium ring were obtained via experiment and numerical simulation as shown in Fig. 7. Fig. 8 shows that the uniform strain of titanium ring increases with the increment of deformation velocity (strain rate).These results indicate that when the deformation speed of the Ti-6Al-4V titanium alloy is 2mm/min (i.e. quasi-static), the strain rate is 6.67×10^{-4} 1/s and its uniform strain (ε_u) is 0.102, while the uniform strain is only 0.032 when the deformation speed of 46.7 m/s is greater than the quasi-static. However, its uniform strain increases proportionally with the increment of the strain rate. Until the deformation speed is greater than 286 m/s, the uniform strain exceeds the quasi-static uniform strain reaching 0.11 or more, in which the strain rate exceeds 6935.6 1/s. Therefore, the deformation speed of 286 m/s or the strain rate of 6935.6 1/s could be considered as the threshold to improve the ductility of Ti-6Al-4V titanium alloy.

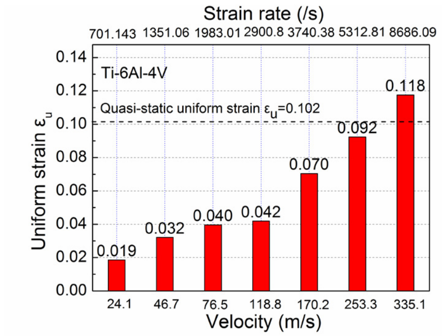

Fig.7. Effects of deformation velocity and strain rate on the uniform strain of titanium ring.

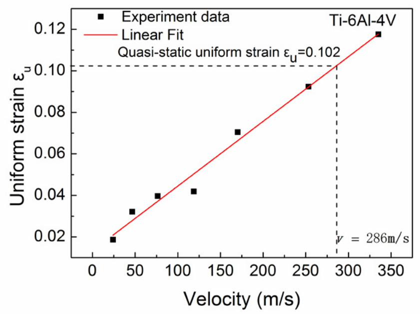

Fig. 8. Uniform strain of Ti ring as function of deformation velocity.

4. Discussion

According to the loading model of the micro-element of the ring specimen in the electromagnetic ring expansion process and taking the circumferential uniformity coefficient of the ring specimen into account, a finite element model was constructed. Based on the calculated data, the variation of circumferential stress and inertial forces with time were obtained and the results are as displayed in Fig. 10. In the elastic deformation stage, no dramatic fluctuation happens in the inertial force of the ring specimen. When reaching the plastic deformation stage, the ring specimen experiences the inertia force changes with small amplitude oscillation. A reverse inertial force is produced when necking happens, which would prevent and distract the necking, thus improving the uniformity of the deformation. Therefore, inhibition of the inertial force in electromagnetic expander is the cause of the fact that the uniform strain increases with the increasing strain rate. This is also in accordance with the literature (Altynova et al., 1996).

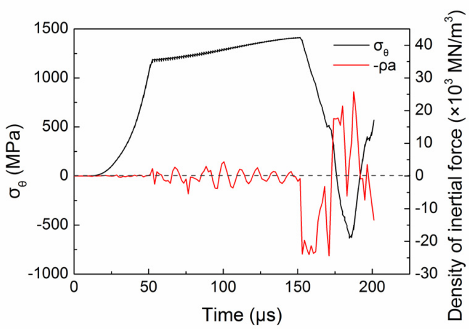

Fig. 10. Circumferential stress and inertial force density as function of time.

Fig. 11 shows the morphology of the fracture of the titanium ring when the discharge voltage and corresponding strain rate are 5.0kV, 76.5m/s and 7.5kV, 335.1m/s, respectively. The fracture of the titanium ring is characterized of scattered and small number of large and deep dimples when the discharge voltage is 7.5kV. While it is quite a different case with a relatively low discharge voltage of 5.5kV. This indicates that there are a lot of positions for the dimple nucleation when the strain rate is low. Lots of micro crack form during the deformation process with fast propagation and the dimple fractures without great plastic deformation. However, the specimen forms less micro crack at higher strain rate, and each dimple experiences great plastic deformation, which can reduce the damage and improve the formability of the sheet.

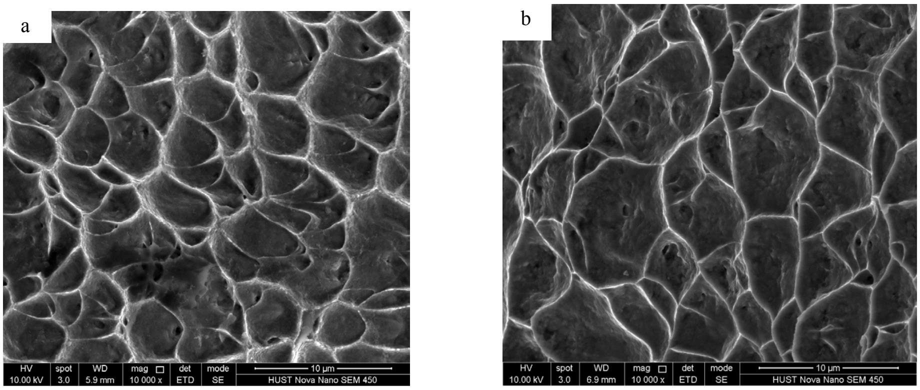

Fig. 11. Scanning topography of Ti ring with discharge voltage (×10000): (a) 5.0kV; (b) 7.5kV.

5. Conclusions

The electromagnetic ring expansions of the Ti-6Al-4V rings with the use of aluminum driver rings were carried out with different discharge voltages and the deformation rates were predicted by a proved numerical simulation method. It is found that when the tensile speed of Ti-6Al-4V titanium alloy sample was 2 mm/min (quasi-static), the strain rate of deformation was 6.67×10^{-4}/s and its uniform strain reached 0.102. But the uniform strain was only 0.032 when the expanding speed of 46.7 m/s was faster than the quasi-static speed. However, its uniform strain increased proportionally with the increment of the strain rate. The uniform strain exceeded the quasi-static uniform strain reaching 0.11 or more until the deformation speed was faster than 286 m/s, in which the strain rate exceeded 6935.6 1/s. Therefore, the deformation speed of 286 m/s or the strain rate of 6935.6 1/s could be considered as the threshold to improve the ductility of Ti-6Al-4V titanium alloy. From the fracture analysis, it could be concluded that the facture of Ti ring at higher speed expansion develops better and shows higher ductility.

Acknowledgements

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