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Dynamic ductility and fragmentation for aluminum alloy using electromagnetic ring expansion

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Abstract

In order to investigate the effects of ductility enhancement for aluminum alloy under the high-velocity EMF condition, the electromagnetic ring expansion test is carried out. Through a use of Photron digital high-speed video camera, the sequence of deformation and failure in the expanding ring are determined. Subsequently, the variation of expansion velocity with time is measured. In particular, this work reveals the effects of expansion velocity on the ductility, necking characteristic, fracture behavior of Al 5052-O and 6061-T4. In addition, the dynamic ductility of Al 5052-O under electromagnetic ring expansion experiment is compared with that in split Hopkinson tension bar (SHTB) test and quasi-static tensile case. It is shown that the number of necks and fragments increase as the maximum expansion velocity increases. Furthermore, the uniform strain and fracture strain augment with increasing expansion velocity, which is more evident for Al 5052-O. The fracture surfaces of ring fragments are characterized by the larger and deeper dimple-like structure at higher expansion velocity. Compared with the SHTB tests at the same strain rate, the ductility of Al 5052-O under electromagnetic ring expansion is better. The ductility enhancement results from not only the inertia effect but also the changes in material constitutive behavior.

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Keywords: Ecletromagnetic ring expansion test; Ductility; High strain rate deformation; Fragmentation

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1. Introduction

Many engineering applications may benefit from a better understanding of the influence of deformation velocity on materials ductility. The electromagnetic forming (EMF) process is an attractive manufacturing technique, which uses electromagnetic body forces to shape metallic parts. The most important advantage of the EMF is the obvious increase in lightweight metals which are difficult to deform at room temperature, with aluminum alloy featuring prominently among them. The electromagnetic ring expansion experiment is utilized as the tool for examining dynamic ductility behaviour of materials.

Experimental investigation of tensile fracture and fragmentation response at high strain rates was pioneered by Niordson (1965), who designed an electromagnetic loading scheme to drive the ring expansion arrangement. The capability of the ring expansion method was fully exploited by Grady and Benson (1983) who performed numerous experiments on OFHC copper and 1100-O aluminum. In their study, the total length of all ring fragments was calculated for the fracture strain. Altynova et al. (1996) confirmed the increase in ductility of OFHC copper and Al 6061, however, besides the definition of fracture strain proposed by Grady and Benson (1983) there was also used a cross-sectional area change in the uniform portion of fragments as a parameter determined materials ductility. In recent times the behaviour of ductile materials was widely studied by Zhang and Ravi-Chandar (2008). An innovative high-speed camera system was used to obtain images which show the ring deformation and failure process. They found that fracture strain has nothing to do with the ductility of the materials and strain rate effects do not appear to be important for the aluminum alloy Al 6061-O. Janiszewski (2012) carried out electromagnetic ring expansion experiments at room and low temperature conditions on Cu-ETP, Al 7075, barrel steel and tungsten alloy to study the variation of ductility with expansion velocity.

On the other hand, the tests based on the split Hopkinson bar have been used successfully to determine the ductility properties of materials at high strain rates from 10^2 to 10^4 s^{-1} (Ma et al., 2014).

Accordingly, this work investigates the effects of expansion velocity on the ductility, necking characteristic, fracture behaviour of Al 5052-O and 6061-T4. Furthermore, the dynamic ductility of Al 5052-O under electromagnetic ring expansion condition is compared with that in SHTB test and quasi-static tensile case.

2. Experimental procedure

2.1. Specimen preparation

Ring-shaped specimens with inner and outer diameters of 65 and 67 mm and height of 1mm were prepared for aluminum alloy 5052-O and 6061-T4 in order to perform the electromagnetic ring expansion experiment. Quasi-static tensile tests were performed on an AG-100KN testing machine using specimens with geometry presented in Fig. 1(a). The strain rate was maintained at 0.001 s^{-1}. Another dynamic tensile tests for comparative purposes were carried out on a split Hopkinson tension bar (SHTB) using specimens with geometry presented in Fig. 1(b).

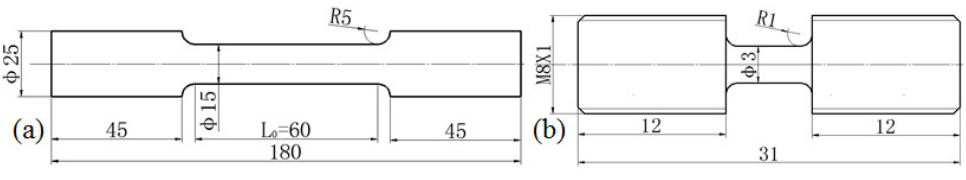
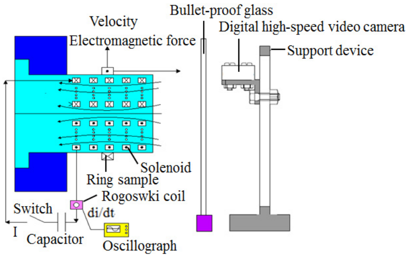


Fig. 1. Configurations of specimens under quasi-static tests and SHTB tests (in mm).

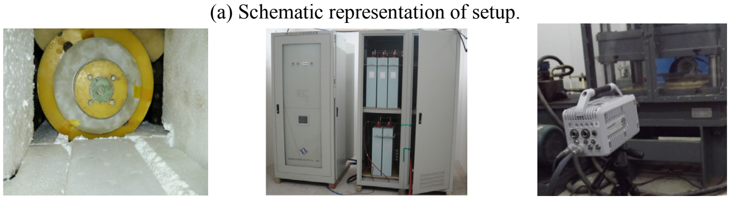
2.2. Setup for electromagnetic ring expansion

The schematic representation of experimental setup for electromagnetic ring expansion test is shown in Fig.2(a). An axisymmetric aluminum ring is placed outside a fixed coil (Fig. 2(b)) which is connected to a 213μF capacitor (Fig.2(c)) that can be charged to a maximum voltage of 25 kV. Upon the capacitor's discharge, the time-varying current in the coil induces a large current in the ring specimen and the resulting Lorentz forces make it expand.

Then, through a use of Photron digital high-speed video camera (Fig. 2(d)), the sequence of deformation and failure in the expanding ring are determined. In the present investigation, at least five ring specimens were carried out under the same loading condition, for example, the same discharged voltage.



(a) Schematic representation of setup.



(b) Coil. (c) Electromagnetic pulse power system. (d) Digital high-speed camera.

Fig. 2. Experimental setup for electromagnetic ring expansion experiment.

2.3. Measure of ductility

To measure the ductility of tested materials, uniformed strain ε_u was calculated of cross-sectional dimensions of recovered ring fragments using the following equation: $\varepsilon_u = (A_0 - A)/A$ whereA0 and A are the initial and the uniform deformed cross-sectional areas, respectively. On the other hand, the final logarithmic ring strain at failure ε_f was determined for comparison. It should be clearly emphasized that the materials ductility cannot be expressed by ε_f, since this parameter is dependent on the geometry of the ring samples investigated by Zhang et al. (2008).

The fracture morphology of the specimens under electromagnetic ring expansion experiment, SHTB test and quasi-static condition were examined by JSM-7600F field emission scanning electron microscope with an operating voltage of 15 kV. Finally, the specimens under different loading conditions were put on a micro Vickers with 9.8N loading force maintaining 20 s to get the micro-hardness for studying the effect of ductility enhancement.

3. Results and discussion

Fig. 3 reveals the sequence of images showing expansion of an Al 5052-O specimen (charge voltage 6.5 kV) obtained at 10μs intervals. An abrupt change of slope in the specimen current is at some time between 90 and 110μs for Al 5052-O, which is also the moment that the maximum velocity occurs; we identify from high speed images that this corresponds to the first fracture in the ring. The first fracture occurs while a high current is still circulating in the ring and as a result, electric arcs emerge at fracture points. In Fig.3 there can be also observed that the fragmentation process is preceded by strain localization, which is expressed through multiple necks occurring evenly at the ring circumference. It should be noted that not all necks become the onset of ring fractures.

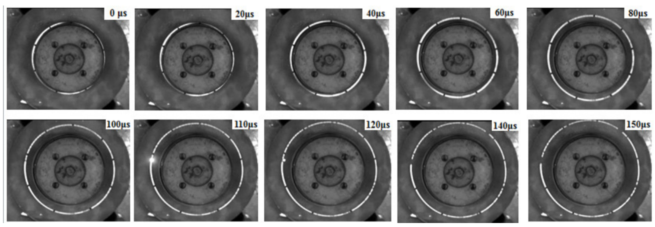


Fig. 3. Sequence of images showing the expansion of an Al 5052-O ring specimen (maximum expansion velocity 90 m/s).

For Al 5052-O and 6061-T4, numerous necks are visible both near the regions of fracture nucleation and in the middle part of ring fragments. The influence of the maximum expansion velocity on the number of fragments and necks is shown in Fig. 4. The results reveal that for both the two aluminum alloys, the number of fragments and necks augment with increasing maximum expansion velocity. Considering the fact that some necks do not proceed to final failure, there are always more necks than fragments.

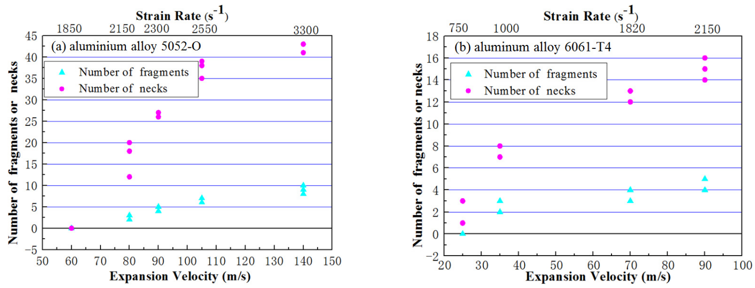


Fig. 4. Influence of expansion velocity on the number of fragments and necks for Al 5052-O and 6061-T4.

Ductility behavior at electromagnetic ring expansion for the two aluminum alloy ring specimens is illustrated in Fig. 5, showing that uniform strain ε_u increases as the maximum expansion velocity increases. The data obtained in quasi-static tensile tests are also included in this figure. It is evident that uniform strains are considerably improved at high velocities for Al 5052-O when the velocity reaches 90m/s, whereas Al 6061-T4 reveals a drop in ductility compared to the quasi-static one. It seems to result from strengthening effect which will be furthered discussed in the analysis of micro-hardness of the ring fragments.

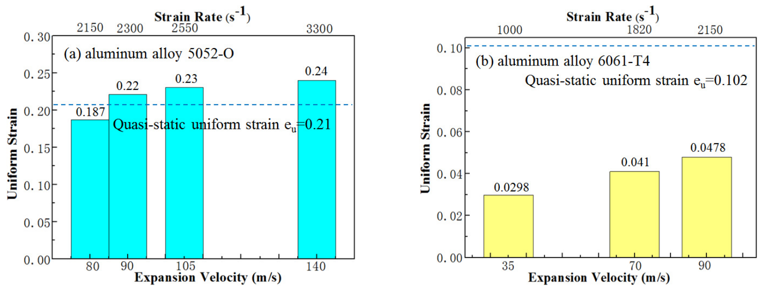


Fig.5. Influence of expansion velocity on uniform strain ε_u for Al 5052-O and 6061-T4.

For comparative purposes, fracture strain ε_f is presented in Fig. 6. As mentioned earlier, elongation at fracture ε_f cannot measure the ductility of plastic materials. However, this parameter is good at characterizing the materials ductility at high strain rate. The fracture strain increases with increasing expansion velocity and it is generally greater than the uniform strain ε_u measured by reduction in the area in the uniform deformed region, especially for the Al 6061-T4, which is due to excess strain in the necked parts of the ring fragments.

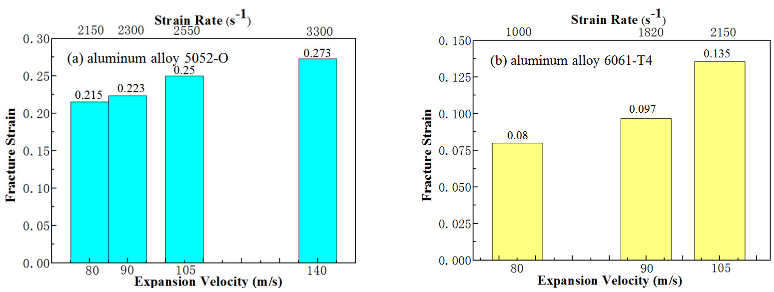


Fig.6. Influence of expansion velocity on fracture strain ε_f for t Al 5052-O and 6061-T4.

Improved ductility in rapidly ring expansion tests may result from two separate effects: inertia and changes in material constitutive behaviour at high strain rates (Altynova et al., 1996). As a simple test to see how velocity may have affected the material flow behaviour, microhardness was measured as a function of the maximum expansion velocity, which is illustrated in Fig.7. The visible increase in hardness of ring fragments is observed for the two aluminum alloys and the hardness of Al 5052-O increases with increasing expansion velocity. When the maximum velocity reaches 140 m/s, the hardness of Al 5052-O is 40.35% higher than that of the original one and 33.33% higher than that in quasi-static case. Moreover, the hardness of Al 6061-T4 exceeds the original value by 55%. In addition, the hardness of Al 6061-T4 is much higher than that of Al 5052-O at the same expansion velocity or strain rate, indicating the more evident strengthening effect due to the microstructure form of Al 6061-T4 which consists of strengthening precipitates, such as the Mg_2Si. These dispersed in the aluminum matrix cause reinforcement of the materials, that is, the strength properties increase, while the ductility is reduced as mentioned above. These results reveal that besides inertia effects, the changes in material constitutive behaviour could be responsible for improved ductility of Al 5052-O and 6061-T4, which confirms the previous observation made by Jacek Janiszewski (2012) and questions the conclusion drawn by Zhang and Ravi-Chandar (2008) .

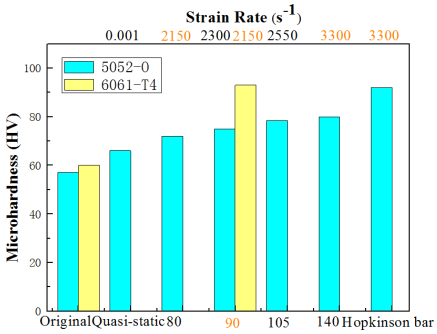


Fig.7. Vickers micro-hardness of specimens under different loading conditions.

In particular, since electromagnetic ring expansion tests and the split Hokinson tension bar (SHTB) tests are both the experiments examining the dynamic ductility of materials, the hardness of specimens for Al 5052-O under SHTB tests was measured for comparison, which can be also observed in Fig. 7. At the same strain rate, the hardness of specimens under SHTB tests is higher than that of electromagnetic ring expansion conditions, indicating SHTB tests bring more reinforcement to Al 5052-O.

In order to further analyze the ductility behavior and fracture characteristic, the SEM fractographs of the deformed Al 5052-O specimens under electromagnetic ring expansion and quasi-static tests were observed, as shown in Fig.8. It is noted that the dimples in dynamic fracture zone are larger and deeper than those in the quasi-static one, meanwhile the increase of the size and depth of dimples is evident with increasing expansion velocity, revealing that the ductility of Al 5052-O is enhanced by electromagnetic ring expansion tests.

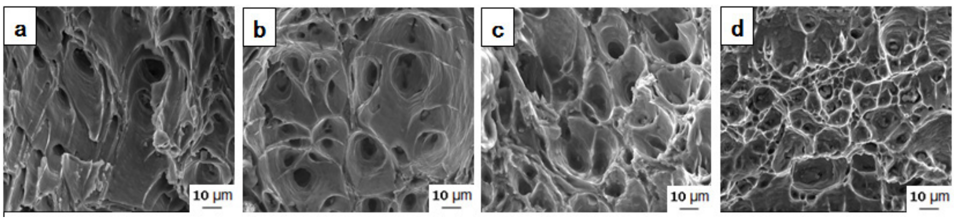


Fig.8. SEM images showing the fracture surfaces of specimens under electromagnetic ring loading tests at different velocity and strain rate: (a) $v = 90m/s, \dot{\varepsilon} = 2300^{-3}s^{-1}$; (b) $v = 105m/s, \dot{\varepsilon} = 2550s^{-1}$; (c) $v = 140m/s, \dot{\varepsilon} = 3300s^{-1}$; (d) $\dot{\varepsilon} = 0.001s^{-1}$.

SEM images showing the fracture surfaces of specimens under different loading conditions are presented in Fig. 9. As can be seen, the dimples are bigger and more homogeneous under electromagnetic ring expansion tests compared with the SHTB cases and quasi-static condition, indicating the better ductility of Al 5052-O is obtained using electromagnetic ring expansion.

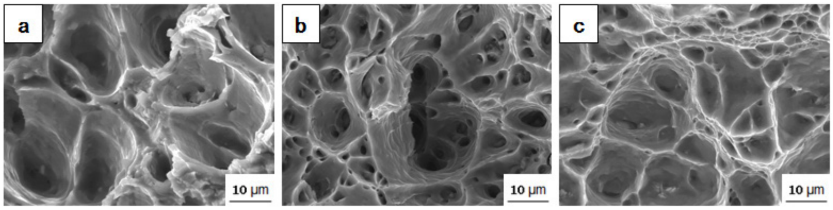


Fig.9. SEM images showing the fracture surfaces of specimens under different loading conditions: (a) electromagnetic ring test, $\dot{\varepsilon} = 3300s^{-1}$; (b) split Hopkinson tension bar test, $\dot{\varepsilon} = 3300s^{-1}$; (c) quasi-static tension test, $\dot{\varepsilon} = 0.001s^{-1}$.

4. Conclusion

The effects of expansion velocity on the ductility and fracture behavior of Al 5052-O and 6061-T4 under electromagnetic ring expansion condition are investigated. The main findings can be summarized as follows.

(1) Multiple necks nucleate evenly along the circumference of the ring and the number of necks and fragments increase as expansion velocity increases for Al 5052-O and 6061-T4.

(2) The uniform strain and fracture strain augment with increasing expansion velocity. The uniform strain of Al 5052-O under electromagnetic ring expansion exceed the quasi-static value as long as the maximum expansion velocity is higher than 90 m/s, whereas in the case of Al 6061-T4, this effect is not found.

(3) The average hardness of fragments is enhanced as expansion velocity increases and higher than the quasi-static value, which is more evident for Al 6061-T4，indicating that besides inertia effects, the changes in material constitutive behaviour could be responsible for improved ductility of Al 5052-O and 6061-T4.

(4) The fracture surfaces of Al 5052-O ring fragments are characterized by the larger and deeper dimple-like structure at higher expansion velocity.

(5) Compared with the split Hopkinson tension bar (SHTB) tests at the same strain rate, the hardness of Al 5052-O under electromagnetic ring expansion loading is lower while the dimples are bigger and more homogeneous, indicating the better ductility of Al 5052-O is obtained under electromagnetic ring expansion test.

Acknowledgements

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References

Niordson, F.I., 1965. A unit for testing materials at high strain rates. Experimental Mechanics 5 (1) 29-32.

Grady, D.E., Benson, D.A., 1983. Fragmentation of metal rings by electromagnetic loading. Experimental Mechanics,23 (4), 393-400.

Altynova, M., Hu, X., Daehn, G.S., 1996. Increased ductility in high velocity electromagnetic ring expansion. Metallurgical and Materials Transactions A 27 (7), 1837-1844.

Zhang, H., Ravi-Chandar, K., 2008. On the dynamics of necking and fragmentation-II. Effect of material properties, geometrical constraints and absolute size. International Journal of Fracture 150 (1-2), 3-36.

Jacek Janiszewski, 2012. Ductility of selected metals under electromagnetic ring test loading conditions. International Journal of Solids and Structures 49, 1001-1008.

Huijuan Ma, Liang Huang, Yi Tian, Jianjun Li, 2014. Effects of strain rate on dynamic mechanical behavior and microstructure evolution of 5A02-O aluminum alloy. Materials Science and Engineering: A 606, 233-239.