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Frictional effect of ultrasonic-vibration on upsetting

Jung-Chung Hung [a], Yu-Chung Tsai [b], Chinghua Hung [b,*]

[a] Department of Mechanical Engineering, National Chin-Yi Institute of Technology, Taiwan, ROC
[b] Department of Mechanical Engineering, National Chiao Tung University, Taiwan, ROC

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Abstract

The ultrasonic-vibration ring compression test and finite element analysis were performed on aluminum alloy specimens to explore the frictional effect of superimposing ultrasonic-vibration during upsetting. The extrapolated compression test was first adopted to obtain the frictionless material properties for finite element analysis. Experimental results of extrapolated compression test also indicate that ultrasonic-vibration can reduce the compressive force when friction is eliminated and can increase the temperatures of a material at the same time.

The following results of the hot extrapolated compression test and the hot ring compression test reveal that increasing temperature by ultrasonic-vibration may reduce the flow stress and increase the interfacial friction. Finally, finite element analysis was conducted to derive the friction calibration curves and to evaluate the friction factor.

Keywords: Ultrasonic-vibration; Extrapolated compression test; Hot ring compression; Interfacial friction; Aluminum alloy; Finite element simulation

1. Introduction

Interesting effects occur when ultrasonic-vibrations are applied in the metal forming processes, including a reduction in the friction between the die and the workpiece, a decrease in the forming forces and a decrease in the spring-back angle. These effects increase the forming abilities of materials. Blaha and Langenecke were the first to study the effect of ultrasonic-vibration on the plasticity of metals [1,2]. In the experiment, they observed a substantial reduction in the yield stress and the flow stress. This phenomenon is so-called Blaha effect.

Friction between the workpiece and the tooling plates plays an important role in many forming processes, such as forging, extrusion and rolling. Friction affects the deformation load, the surface quality of the product and the internal structure of the product. The friction can also strongly affect the flow of metal and the generation of defects. Friction models in metal forming processes can be categorized into constant shear friction model ($f_s = mk$, f_s is friction shear stress, m is friction factor and k is shear strength of the deforming material) and Coulomb friction model $f_s = \mu p$, μ is coefficient of friction and p is compressive normal pressure). Most forming studies indicate that the constant shear friction model adequately represents the friction model in bulk forming processes while Coulomb friction model is commonly used for representation of friction in sheet-metal forming. A reason for this is that the compressive normal stress at the interface in sheet-metal forming is much smaller in magnitude, in comparison with that in bulk deformation. Among the methods for measuring the coefficient of friction (μ) or friction factor (m), the ring compression test has been widely accepted over the last two decades [3–5]. The ring compression test involves the compression of a ring-shaped specimen by a simple open die. When the ring specimen is plastically compressed between two flat platens, increasing friction results in an inward flow of the material, while decreasing

* Corresponding author. Tel.: +886 3 5712121x55160; fax: +886 3 5720634.
E-mail address: chhung@mail.nctu.edu.tw (C. Hung).

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friction results in an outward flow of the material as schematically shown in Fig. 1 [6]. Male [7] experimentally obtained a set of calibration curves in terms of the reduction in the inner diameter and the reduction in the height of the ring, from which certain coefficient of friction could be derived.

Lehfeldt [8] studied the influence of ultrasonic-vibration on friction, by placing a ball on a revolving plate and exciting it by ultrasonic-vibration. The frictional force was minimum at the contact surface when the direction of vibration was parallel to the direction of motion. Siegert [9] studied the influence of friction on the strip-drawing processes by superimposing ultrasonic-vibration on the die, and showed that the friction forces could be reduced and the surface quality of products could be improved. Prior studies [10] have proven that axial ultrasonic-vibration can reduce the deformation resistance in hot upsetting, and that the effect of ultrasonic-vibration on hot upsetting cannot be explained by only a simple mechanism, such as the effect of interface friction, the superposition of stress, or the absorption of the ultrasonic-vibration energy by dislocations.

During the upsetting process, frictional conditions can strongly affect compressive forces. The increase in frictional forces with the ratio of the initial diameter to the initial height (d_0/h_0) causes higher loads to be required in upsetting. The effect of friction must be removed to obtain accurate stress–strain curves of the material. It can be removed using the extrapolated compression test proposed by Cooke [11].

Most current research on ultrasonic-vibration metal forming is confined to the ultrasonic-vibration drawing and uses the ultrasonic-vibration to improve the lubrication conditions and reduce the drawing force [12–15]. Very few investigations have addressed the frictional effect of ultrasonic-vibration on upsetting. Therefore, the extrapolated compression tests with or without heating were performed on aluminum alloy specimens to obtain the stress–strain relation under ultrasonic-vibration. Additionally, finite element simulations and experiments were conducted, involving hot ring compression tests, to explore the frictional effect of ultrasonic-vibration on upsetting.

2. Extrapolated compression test

2.1. Experimental conditions

The specimens adopted in this study were aluminum alloy A6061; had heights of 3 mm, 4 mm and 6 mm (equivalent to an initial diameter to initial height ratio, d_0/h_0 of 2, 1.5 and 1) and diameters of 6 mm. The compression force was set between 5000N and 18 000N, and the rate of compression was a constant 1 mm/min throughout the experiment. During exposure to ultrasonic-vibration in the extrapolated compression test, the axial vibration frequency was kept at 20 kHz and the amplitude was set to 5.6 μm.

2.2. Experimental results

Fig. 2 plots the experimental strain vs. d_0/h_0 results of both the conventional compression test (CC) and the axial ultrasonic-vibration compression test (AUC). The environmental temperature was set to 25 °C. In Fig. 2a and b, the data points for each compressive force are extrapolated to obtain strain values at $d_0/h_0 = 0$. Under this fictitious geometrical condition, no friction exists and the stress associated with the deformation at this point is a function only of the material's resistance to flow.

Fig. 3 compares the stress–strain curves for CC and AUC under frictionless conditions. It shows that ultrasonic-vibration effectively reduces the material flow stress when the effect of friction is negligible. Therefore, mechanisms other than friction should be responsible for ultrasonic-vibration's reducing the flow stress.

Fig. 4 plots the stress–strain curves obtained from extrapolated compression tests on AUC at 25 °C and CC at four temperatures. The true stress–strain curve of CC at 150 °C was very similar to that of AUC at 25 °C. There-

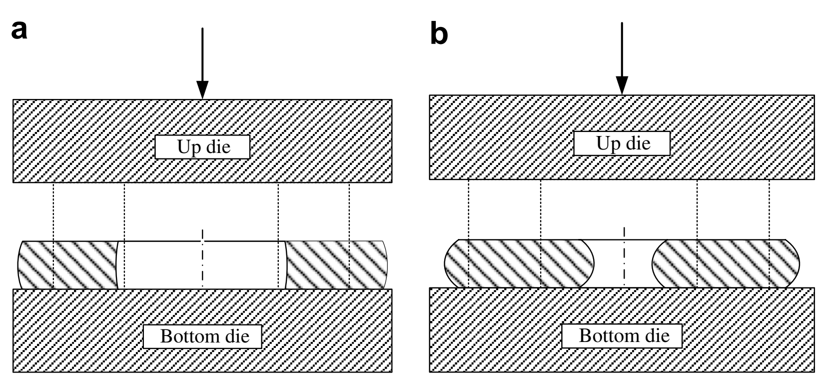

Fig. 1. Material flow during the ring compression test: (a) low friction and (b) high friction.

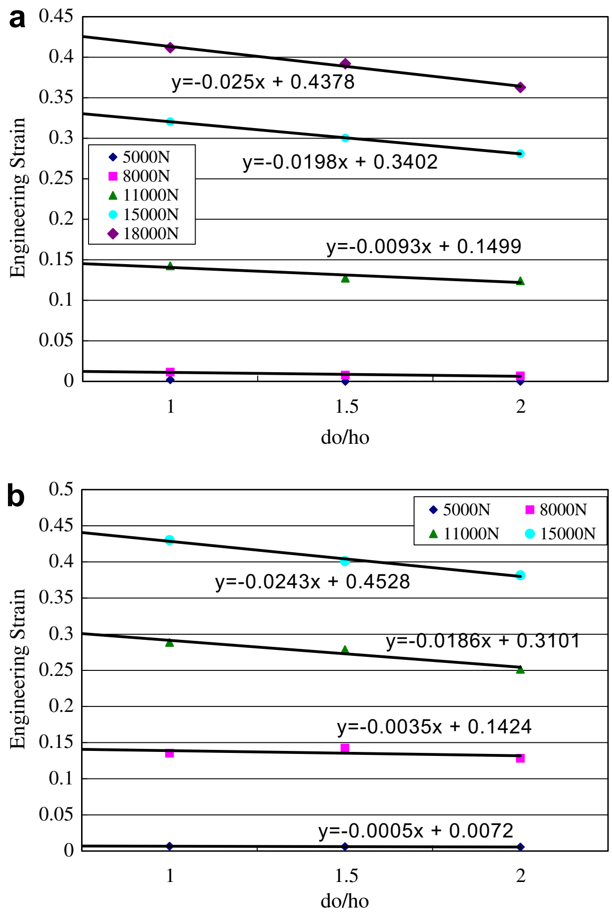

Fig. 2. Experimental results of strain vs. d_0/h_0 plots for CC and AUC: (a) extrapolation to zero d_0/h_0 for compressive strain of CC and (b) extrapolation to zero d_0/h_0 for compressive strain of AUC.

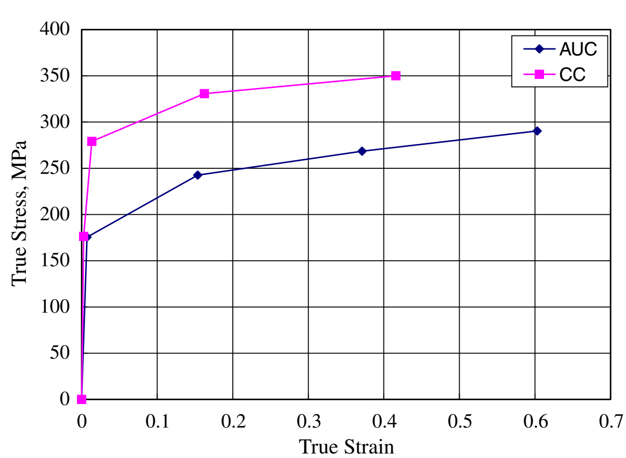

Fig. 3. The stress–strain curves in frictionless condition for CC and AUC at 25 °C.

fore, the reduction in the flow stress caused by increasing the temperature to 150 °C is similar to that caused by applying ultrasonic-vibration.

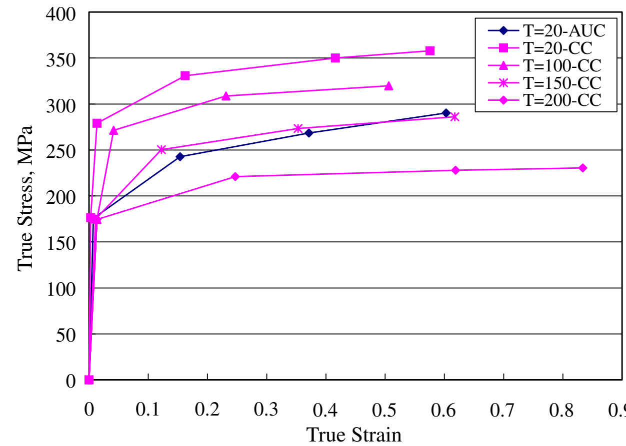

Fig. 4. The stress–strain curves in frictionless condition effect for HCC and AUC at 25 °C, 150 °C and 200 °C.

2.3. Temperature measurements during ultrasonic-vibration on upsetting

During the compression test, the material vibrated at high speed, so were a thermocouple to have been inserted into the specimen, the generated heat caused by the rubbing may have damaged the thermocouple and generate errors in the readouts. An IR thermometer (Raytek MX4) and a film-type thermocouple (ANRITSU ST-24K) were adopted to measure indirectly the average temperature during AUC tests to overcome these difficulties. Specially designed specimens with a thin (0.2 mm) wing were made to attach film-type thermocouples, as shown in Fig. 5.

Fig. 6 plots the results of temperature measurement with $d_0/h_0 = 2, 1.5, 1$ in AUC tests. The temperatures measured using the film-type thermocouple exceeded those measured using the IR thermometer because the IR thermometer measured only the average temperature at the focal spot, which had a diameter of 6 mm. The test results indicated that ultrasonic-vibration indeed raised the temperature of the material, and that smaller specimens had higher temperature. The temperature increased rapidly in the initial vibration stage and then decreased with time.

3. Ring compression test

3.1. Experimental procedures

The procedures of a hot ring compression test were as follows. Initially, the ultrasonic-vibration system and a vacuum furnace were established on a hot bench controlled by a microcomputer server. Secondly, the ring specimen was placed between parallel dies and a 200N preload was applied to the ring specimen. The heating controller was turned on. When the temperature reached the designated temperature, it was held constant for 10 min before the experiment was performed. Whenever the loading reached 700N during an experiment, ultrasonic-vibration was applied. When the compression was finished, the

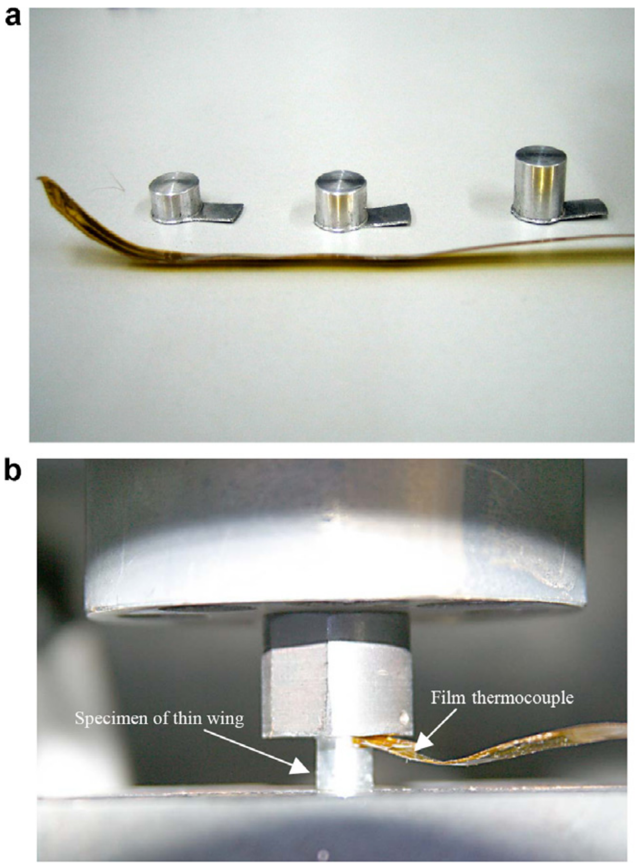

Fig. 5. Temperature measurements of ultrasonic-vibration on upsetting: (a) the specimens with thin wing and film-type thermocouple and (b) experimental set-up for temperature measurements.

deformation of the ring specimen was measured before the specimen was removed from the platens.

3.2. Experimental conditions

Table 1 shows the material properties and the hot ring compression test conditions used in the experiments. During these tests, the compression strain was set between 10% and 50% and the compression rate set to a constant 1 mm/min for both conventional ring compression (CRC) and hot ring compression (HRC). In HRC, the temperatures were set to 150 °C and 200 °C. The ring specimens adopted in this study were made from aluminum alloy A6061; the external and internal diameters of the ring were 6 mm and 3 mm, respectively, and the height was 2 mm. The tests were performed without lubricant. During ultrasonic-vibration ring compression (AURC), the axial vibration frequency was kept at 20 kHz and the amplitude was set to 5.6 μm.

3.3. Experimental results

Fig. 7 plots experimental friction calibration curves of CRC and AURC at 25 °C. When the height was reduced by 50%, the reduction of inner diameters was 32.7% in CRC and 53.8% in AURC. This figure clearly shows that in ultrasonic-vibration upsetting, the increase of reduction of inner diameter may be caused by the increase of friction at the interface.

Fig. 8 plots the experimental friction calibration curves for ring compression at 25 °C, 150 °C and 200 °C. These curves indicate that the friction in the interface increases with the temperature.

Fig. 9 shows the final profiles of the specimen for CRC, HRC and AURC. In the HRC and AURC cases, the outside and inside diameters are smaller than those in the CRC case for the same degree of compression, as shown in Fig. 9b and c. Because the reduction of inner diameter of ring specimens is an indication of friction value, the friction increases in cases of both HRC and AURC. Furthermore, the cross-sectional profiles in Fig. 10 reveal that the deformation patterns are very similar for AURC at 25 °C and HRC at 200 °C.

As shown in Fig. 11, the calibration curve of AURC at 25 °C is closer to that of HRC at 200 °C, indicating that the friction condition under ultrasonic-vibration at 25 °C is very similar to that at 200 °C without ultrasonic-vibration. This result differs from that of the extrapolated compression tests, that the stress–strain relationship under ultrasonic-vibration is equivalent to that at 150 °C without ultrasonic-vibration. This discrepancy may result from the fact that the specimens in ring compression are smaller than those in extrapolated compression tests, so the absorption of vibrating energy and the increase in temperature is larger in ring compression tests.

3.4. Finite element analysis of ring compression

The ring compression tests were also analyzed using the FEM code Deform 2D. Fig. 12 shows the axisymmetric FEM analysis model used in this study and Table 2 shows the conditions adopted in the analysis. During the simulation of HRC, the material of the specimen used for compression was defined as a rigid-plastic body and the dies were defined as rigid bodies. The material properties used in the analysis were obtained from the experimental results on CC at different temperatures. The friction factor (m) for the interfacial friction between die and specimen was used, and a constant compression rate of 1 mm/min was set.

Fig. 13 plots the friction calibration curve for FEM analysis and the experimental results at 25 °C. The data points represent the experimental results for CRC and AURC without lubricant. The friction factor of CRC is around 0.4. The friction factor of AURC was increased to over 1.

Fig. 14 plots the friction calibration curve for FEM analysis and the experimental results at 200 °C. The data points represent the experimental results for CRC at 200 °C and AURC at 25 °C without lubricant. The friction factor was increased to 0.8 with CRC at 200 °C. The friction factor of AURC was increased and also exceeds 1. The results indicate that the increase of reduction of inner

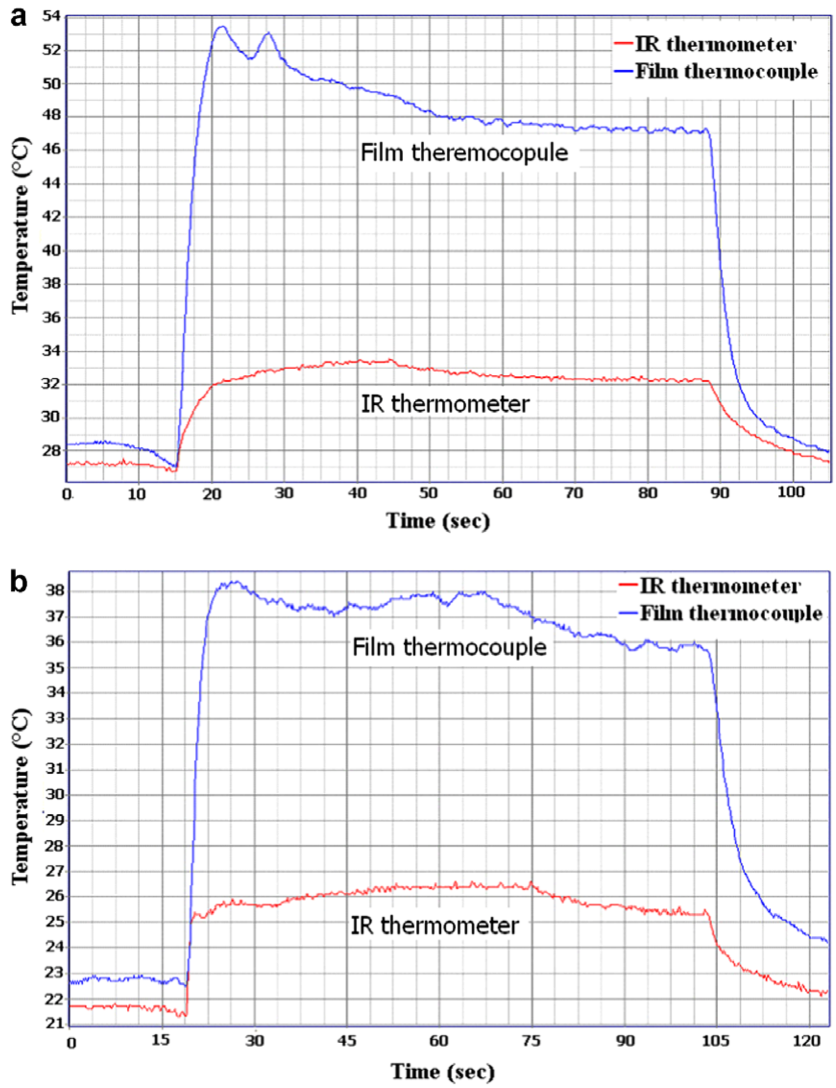

Fig. 6. Results of temperature measurement for AUC: (a) temperature measurement for d_0/h_0=2 with 11 000N compressive force, and (b) temperature measurement for d_0/h_0=1 with 11 000N compressive force.

Table 1
Material and compressive conditions

Specimen material	Aluminum alloy (A6061)
Tooling material	Stainless steel (SUS304)
Size of specimen	$\phi 6.0 \times \phi 3.0 \times 2$ mm
Lubricant	N/A
Reduction in height (%)	10, 20, 30, 40, 50
Compression speed	1 mm/min
Temperature of specimen (°C)	25, 150, 200

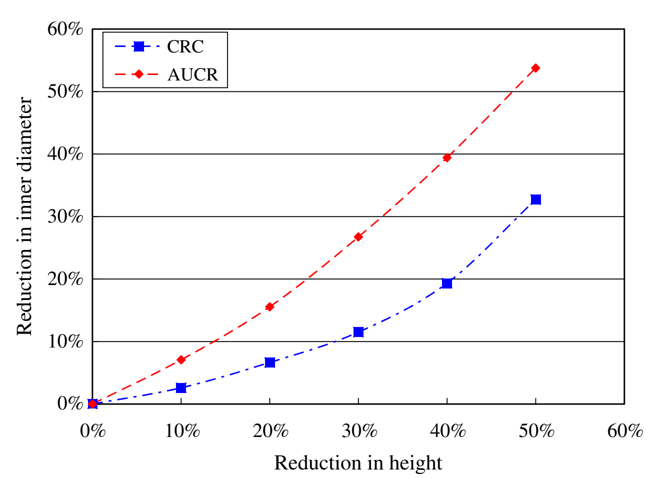

Fig. 7. Experimental friction calibration curve for CRC and AURC at 25 °C.

diameter during ultrasonic-vibration may be caused by the increase in the temperature of the material.

4. Results and discussion

The effect of reducing the flow stress on upsetting during ultrasonic-vibrating is very complicated. Prior studies have established that the mechanism associated with ultrasonic-vibration involved a change of interfacial friction, the

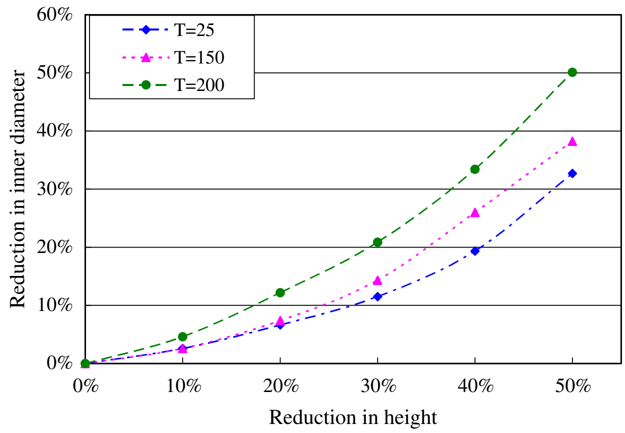

Fig. 8. Experimental friction calibration curve for CRC at 25 °C, 150 °C and 200 °C.

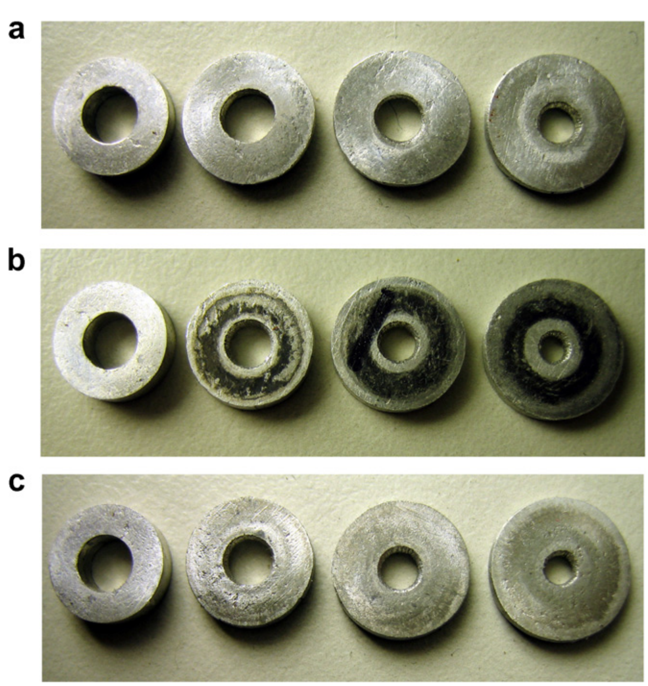

Fig. 9. Final profiles of the specimens for CRC, HRC and AURC: (a) CRC at 25 °C, (b) AURC at 25 °C and (c) HRC at 200 °C.

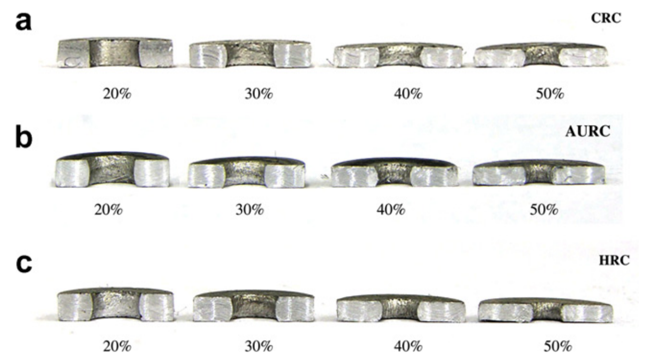

Fig. 10. Cross-sectional profiles of the specimens for CRC, HRC and AURC: (a) CRC at 25 °C, (b) AURC at 25 °C and (c) HRC at 200 °C.

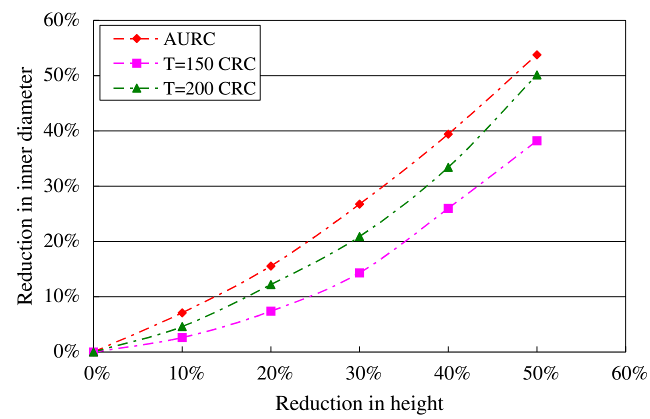

Fig. 11. Experimental friction calibration curve for AURC at 25 °C, CRC at 150 °C and 200 °C.

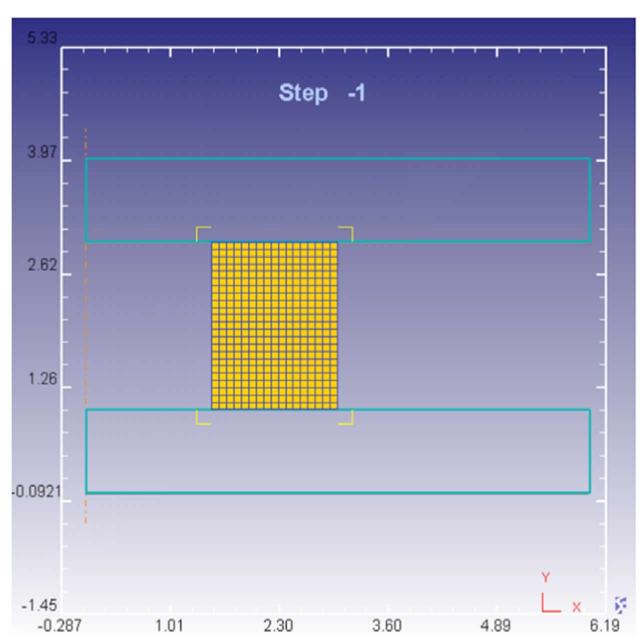

Fig. 12. FEM simulation model of ring compression test.

superposition of stress or the absorption of ultrasonic-vibration energy by dislocations. As shown in Fig. 3, ultrasonic-vibration can still effectively reduce flow stress even when the effect of interfacial friction is excluded. Therefore, the reduction of interface friction was not the major mechanism of flow stress reduction. Additionally, the results of the extrapolated compression test show that the effect of reduction in flow stress caused by the ultrasonic-vibration equals that of raising the temperature to 150–200 °C. This fact reveals that the reduction of flow stress is related to the increase in temperature of the material when the vibration energy is absorbed.

Although the temperature may have risen when the material absorbed the ultrasonic-vibration energy, discrep-

Table 2
FEM simulation conditions

Ring	Plastic deformable body
Die	Rigid body
Simulation model	Axisymmetric model
FEM program	DEFORM 2D
Interaction property	Shear friction factor

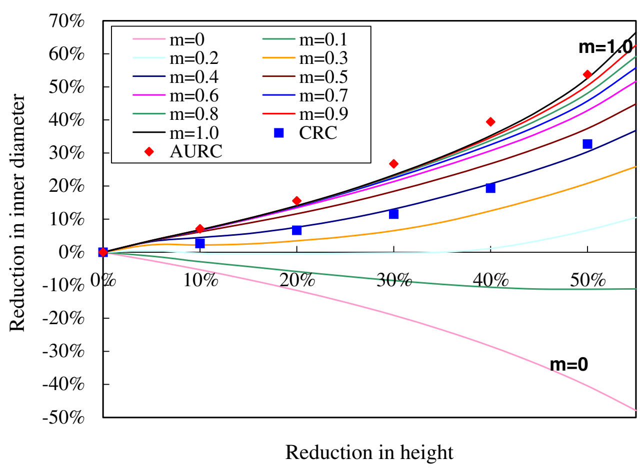

Fig. 13. The friction calibration curve for FEM analysis and experiment result at 25 °C.

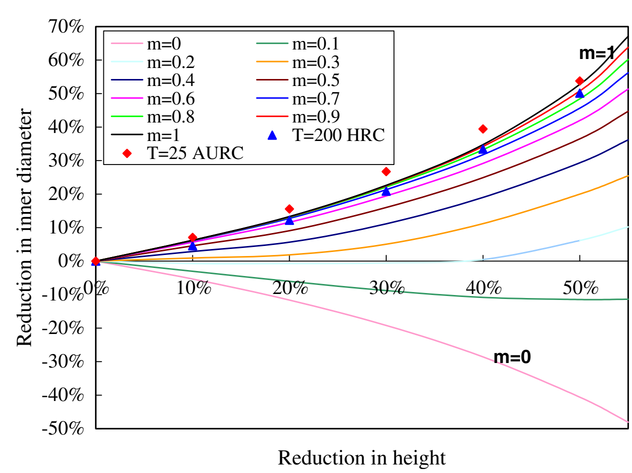

Fig. 14. The friction calibration curve for FEM analysis and experiment result at 200 °C.

ancies were found between the indirect temperature measurement (40–50 °C) and the temperature (150–200 °C) inferred from the results of the extrapolated compression tests. These discrepancies might be associated with the rate of thermal conductivity and thermal dissipation. When ultrasonic-vibration is applied, the material absorbs the energy of vibration and the temperature at the interface between the die and the specimen is instantaneously increased. Aluminum alloy has good thermal conductivity and good thermal dissipation, so when the temperature at the interface increased, the surface of the specimen dissipated heat, creating a temperature gradient within the specimen. Both average and indirect measurements of temperature are lower than actual values, especially much lower than the temperature of the specimen at the interface.

Figs. 13 and 14 show that the increase of reduction of inner diameter was accompanied with raised temperature and the friction factors of AURC exceeded 1. This result reveals that the effect of friction under ultrasonic-vibration exceeds that of CRC under 200 °C, it is because (1) the volume of the specimen used in the ring compression test is smaller than that used in the extrapolated compression test; the amount of vibration energy absorbed per unit volume is larger, and the heat dissipative area is smaller, so the temperature of the specimen is higher; (2) under ultrasonic-vibration, the temperature at the interface exceeds that of the rest of the specimen, so, the friction factor is also higher at the interface.

The output power of the ultrasonic-vibration generator is limited, so experiments must be conducted with smaller specimens. Also, the focal spot of measuring device was too large for temperature measurements in the current experiments. The accuracy of the temperature measurements was limited in this study. In future research, ultrasonic-vibrating apparatus with higher power should be used, so that the experiments with larger specimens could be conducted. More accurate temperature measurement methods should be investigated to determine the real temperature field distribution and the increase in temperature at the contact interface during upsetting with ultrasonic-vibration. The mechanisms of ultrasonic-vibration on upsetting can then be further verified.

5. Conclusions

A finite element simulation and experiments on hot ring compression were conducted to explore the frictional effect of ultrasonic-vibration on upsetting. The results in this study support the following conclusions.

(1) The results of the extrapolated compression experiment show that when friction is negligible, ultrasonic-vibration can still effectively reduce the material flow stress.
(2) The results of the ring compression experiment show that the interface friction increases with the temperature of material.
(3) The results of the ultrasonic-vibration ring compression experiment indicates that ultrasonic-vibration increases the interfacial friction.
(4) The temperature measurements indicate that ultrasonic-vibration increased the temperature of the material.
(5) The size of the specimen affects the increase in temperature caused by the ultrasonic-vibration. More precise apparatus are required to measure accurately the magnitude and the distribution of temperature caused by ultrasonic-vibration on upsetting.

Acknowledgements

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