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Investigations on the material property changes of ultrasonic-vibration assisted aluminum alloy upsetting

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ABSTRACT

Numerous studies have shown the benefit of ultrasonic-vibration assisted metal forming. This benefit include a reduction in forming forces, which might be attributed to the superposition of stress, increased temperatures, the effects of interface friction, and energy absorption of dislocation. This study conducts a series of experiments and analyses to investigate the main mechanisms of a reduction in forming forces during ultrasonic-vibration assisted A6061-T6 aluminum alloy upsetting.

The findings of this research confirm that, under frictionless conditions, ultrasonic vibration still reduced forming forces, and ultrasonic vibration can increase the temperature of specimens and soften specimen surface during upsetting. From metallographic analyses and micro-hardness tests, the results reveal that energy absorption of dislocation was occurred during upsetting, which also contribute to the reduction of forming force.

This research concludes that the mechanisms of increased temperatures and energy absorption of dislocation can affect the material property and make a reduction in forming forces; however, the interface friction effect has nothing to do with a reduction in forming forces.

1. Introduction

High-energy ultrasonic waves have been applied to a wide variety of uses, including ultrasonic welding, ultrasonic cutting, ultrasonic metal forming, and ultrasonic die-casting. The process of ultrasonic-vibration assisted metal forming applies ultrasonic energy to a die, which is then used to deform metal specimens. Interesting effects arise when ultrasonic vibration is applied to metal-forming processes, such as a decrease in friction between die and specimen, a reduction in forming forces, and changes in the microstructure of specimens during sheet metal forming. Blaha and Langenecker [1,2] were the first to investigate the use of ultrasonic vibration in relation to the plasticity of metals. They superimposed high-frequency vibrations onto a static load during the tensile test of a zinc single crystal specimen. In their experiment, they observed a substantial reduction in yield stress and flow stress. In similar experiments, flow stress was clearly reduced in polycrystalline materials. The SAE1019 steel experiments showed that applying ultrasonic energy to a specimen increased its temperature, an effect related to the time and amount of ultrasonic energy applied. Microscopic observations showed that grain sizes of materials decreased when ultrasonic energy was applied. The transmission electron microscopy technique (TEM) was used to observe an increase in the density and movement of dislocations after the application of ultrasonic energy to materials.

Abramov [3] investigated the effect of the ultrasonic on the material micro-structural and mechanical properties. It showed that ultrasonically induced stress in NaCl and LiF crystals with the amplitude exceeding their yield strength enhances dislocation density. When the density of the dislocations is high enough, an alignment of dislocations occurs. Kempe [4] proposed three mechanisms by which dislocations absorb energy from vibrations to reduce flow stress: (1) a resonance mechanism, (2) a relaxation mechanism, and (3) a mechanism of simple hysteresis.

Hevill [5] attributed reductions in flow stress to a stress superposition mechanism involving the superposition of steady stress and alternating stress. Our previous study [6] proved that axial ultrasonic vibration could reduce the deformation resistance of materials during hot upsetting. We found that the effect of ultrasonic vibrations on hot upsetting could not be explained by a single simple mechanism, such as the effect of interface friction, the superposition of stress, or the absorption of ultrasonic vibration energy by dislocations.

Substantial research has been conducted on the changes in interface friction in ultrasonic-vibration assisted forming experiments and simulations [7–10]. Huang et al. [11] investigated the benefits of applying the axial ultrasonic vibrations of forming tools

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to an upsetting process using plasticine as a model material to simulate hot metal. In their study, the application of ultrasonic vibration to die reduced the mean forming force during upsetting. The researchers concluded that the stress superposition effect and reductions in interface friction contributed to this phenomenon. Daud et al. [12,13] performed ultrasonic-vibration assisted aluminum alloy compression and tension tests using a piezoelectric force transducer to measure the high-frequency vibration tension and compression force. Furthermore, a finite element model was constructed to describe the effects of superimposing ultrasonic vibration for compression and tension tests. The results indicated that oscillatory stress superposition and contact friction were insufficient to explain the effects of ultrasonic excitation in metal-forming processes.

As mentioned in the literatures, although ultrasonic-vibration assisted forming has been around for decades, the mechanism that induces these effects is still unclear. Explanations on the effects of ultrasonic vibration include the superposition of stress [1,2,5,11–14], increased temperatures [1,2,15], energy absorption of dislocation [3,4], and the effects of interface friction [7–13]. These factors are usually coupled, which makes them difficult to understand. This study conducted a series of experiments and analyses to clearly investigate the main mechanisms of a reduction in forming forces during ultrasonic-vibration assisted A6061-T6 aluminum alloy upsetting. An extrapolated compression test removed the effects of interface friction between the specimens and the die, and a temperature measurement test explored the effects of increased temperatures using an IR thermometer. Finally, this study used metallographic analyses and micro-hardness tests to investigate the effects of energy absorption of dislocation during upsetting.

2. Ultrasonic-vibration assisted extrapolated compression test

To avoid the influence of friction on the measurement of the stress–strain data, Cook and Larke [16] utilized a method of the extrapolated compression test, which applied compression force to cylinder specimens with four different ratios of initial diameter to height (d_0/h_0) from 0.5 to 4 under identical loading conditions. If the diameter of the specimens is kept constant, the height of the specimens increases, resulting in a reduction in interface friction. When the height of specimens approaches infinity, interface friction becomes negligible. The deformation of the cylinder specimens therefore remains uniform during compressions (Fig. 1).

The compression strains obtained with different d_0/h_0 ratios are linear and can be extended to the origin point. When d_0/h_0 reaches 0, the specimen heights are infinite and the effect of interface friction in this strain data becomes negligible. Using this method, additional stain data can be obtained with different loading conditions when d_0/h_0 reaches 0. Based on these steps, stress–strain data under frictionless conditions can be derived.

2.1. Experimental procedure

The procedure for the high-temperature-extrapolated compression test is detailed as follows. The ultrasonic vibration system and a furnace were set up on a hot bench controlled by a microcomputer server, as shown in Fig. 2. The specimens were sprayed with MoS_2 lubricant and placed between parallel dies. A 20 kg preload was applied to the specimens. The heating controller was turned on. When the designated temperature was reached, it was held constant for 10 min before the experiment began. Whenever loading reached 70 kg during an experiment, ultrasonic vibration was superimposed. After compression was complete, deformation of the cylindrical specimens was measured before the specimens were removed from the plates.

Table 1 shows the material properties and the high-temperature-extrapolated compression test conditions used in the experiment. The specimens used in this study were aluminum alloy A6061 with heights of 3 mm, 4 mm, and 6 mm (equivalent to d_0/h_0 of 2, 1.5, and 1, respectively) and fixed diameters of 6 mm. All specimens received T6 treatment, including solution treatment and artificial aging treatment, before the experiment. Fig. 3 shows the microstructure of the specimens with heat treatments before

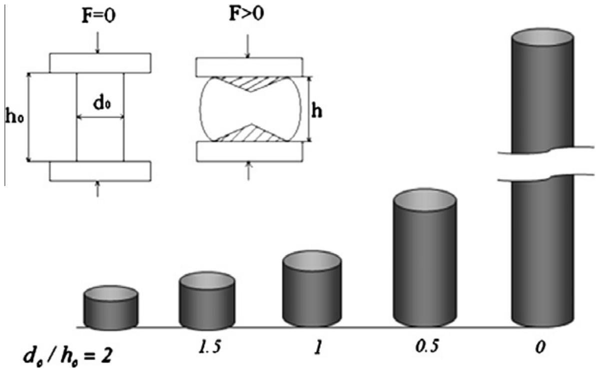


Fig. 1. Barreling of specimens in uniaxial compression.

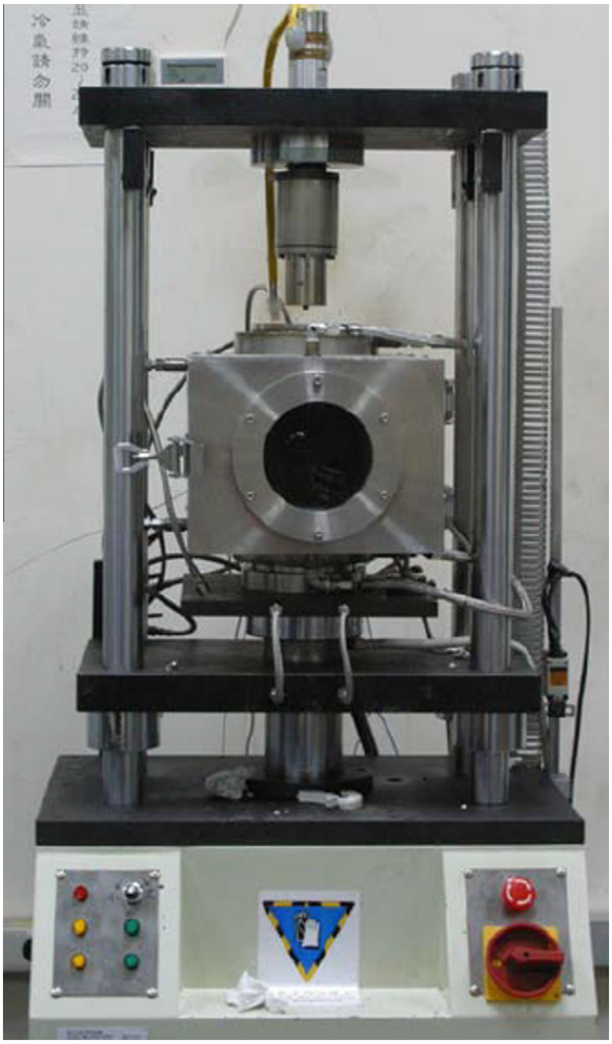


Fig. 2. Ultrasonic-vibration hot upsetting experiment apparatus.

Table 1
Material and compression conditions.

Specimen material	Aluminum alloy (A6061-T6)
Tooling material	Stainless steel (SUS304)
Size of specimens	$\psi 6.0 \times 3.0$ mm, $\psi 6.0 \times 4.0$ mm, $\psi 6.0 \times 6.0$ mm
Lubricant	MoS_2
Compression force	500 kg, 800 kg, 1100 kg, 1500 kg,1800 kg
Compression speed	1 mm/min
Temperature of specimens	25 °C, 100 °C, 150 °C,

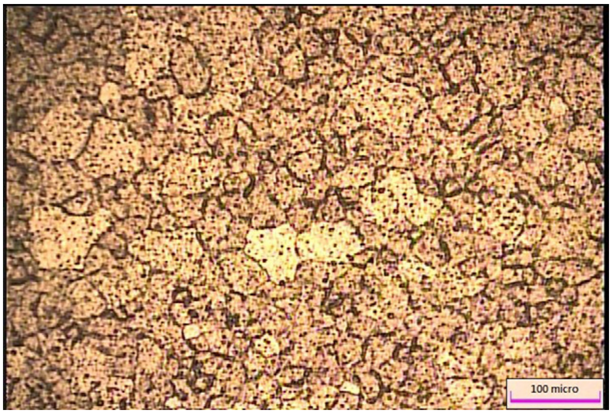


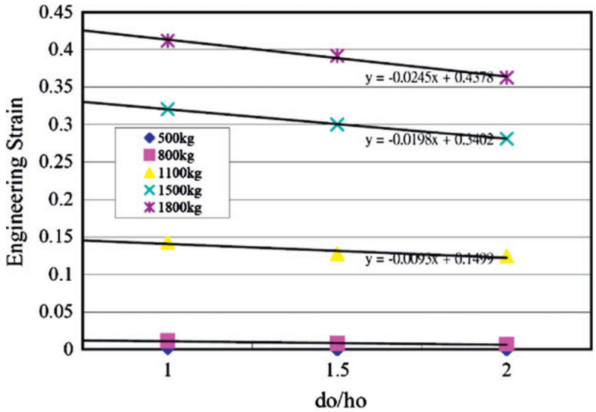
Fig. 3. The microstructure of the specimens with heat treatments before the experiment.

the experiment, and the grain size of the specimens was 22.285 μm. Compression forces were set to 500, 800, 1100, 1100, 1500, and 1800 kg. A constant compression speed of 1 mm/min was maintained throughout the experiment. During the ultrasonic-vibration extrapolated compression test, the axial vibration frequency was maintained at 20 kHz and the amplitude was set to 5.6 μm.

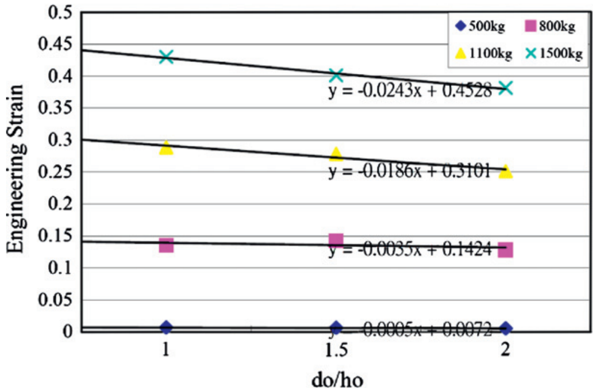
2.2. Experimental results and discussion

Fig. 4 plots the experimental strain vs. d_0/h_0 results of both the conventional compression (CC) test and the axial ultrasonic vibration compression (AUC) test. The environmental temperature was set to 25 °C. Fig. 4a shows the results from CC when compression loading of 500, 800, 1100, 1500, and 1800 kg were applied on specimens with d_0/h_0 ratios of 2, 1.5, and 1. Fig. 4a also shows compression strains under a 500 kg loading condition as 0.00187, 0.00191, and 0.00194 for specimens with d_0/h_0 ratios at 2, 1.5, and 1, respectively. It is therefore difficult to see the data clearly from this figure. The strain when $d_0/h_0 = 0$ can be extrapolated if the strains for specimens with different d_0/h_0 ratios have a linear relationship. This line can then be extended to the origin point. Fig. 4b shows the results from AUC when compression loading of 500, 800, 1100, and 1500 kg were applied to specimens with three different d_0/h_0 ratios. By the comparison between Fig. 4a and b, the engineering strain for AUC with the loading of 1500 kg is higher than that of CC with the loading of 1800 kg. It appears that ultrasonic vibration can significantly reduce the loading. Under these fictitious geometrical conditions with infinity of the height of specimens, no friction occurs and the stress value associated with the deformation is a function only of the material's resistance to flow.

Figs. 5 and 6 plot the stress–strain curves obtained from Fig. 4 for three cylindrical specimens of different initial heights for CC and AUC. Higher loads are required for a higher d_0/h_0. The results show that, under the same loading conditions, flow stress decreased and compression strain increased when d_0/h_0 decreased. This was because interface friction was reduced when d_0/h_0 decreased and specimen height increased.



(a) Extrapolation to zero d_0/h_0 for compressive strain of CC.



(b) Experimental to zero d_0/h_0 for compressive strain of AUC.

Fig. 4. Experimental results of strain vs. d_0/h_0 plots for CC and AUC.

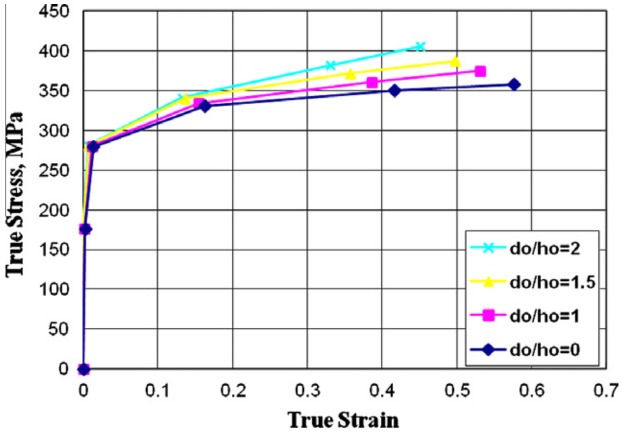


Fig. 5. True stress–strain curves for CC.

Fig. 7 shows a comparison of the stress–strain curves for CC and AUC under frictionless conditions. At the same loading of 1500 kg, true strain in AUC was 18.72% higher than that in CC. True stress in AUC, however, was lower by approximately 59.73 MPa. This shows that ultrasonic vibration can still effectively reduce material flow stress under frictionless conditions. Mechanisms other than friction must therefore be responsible for the reduction in flow stress caused by ultrasonic vibration.

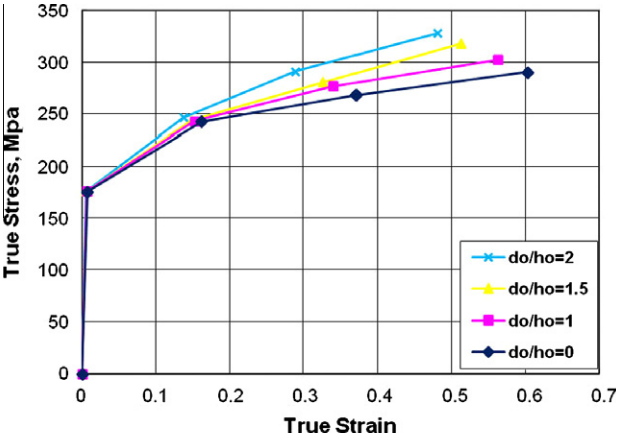


Fig. 6. True stress–strain curves for AUC.

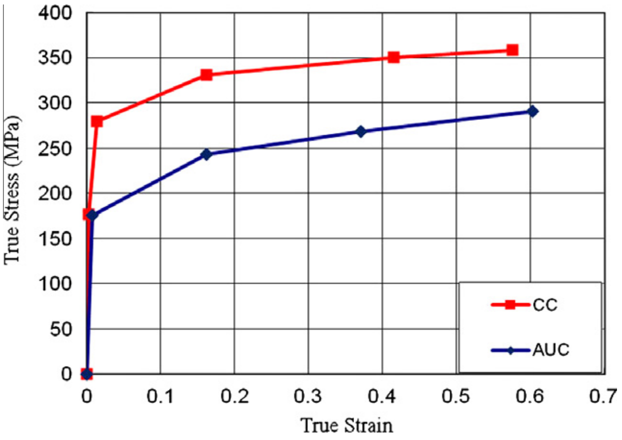


Fig. 7. Stress–strain curves for CC and AUC at 25 °C under frictionless conditions.

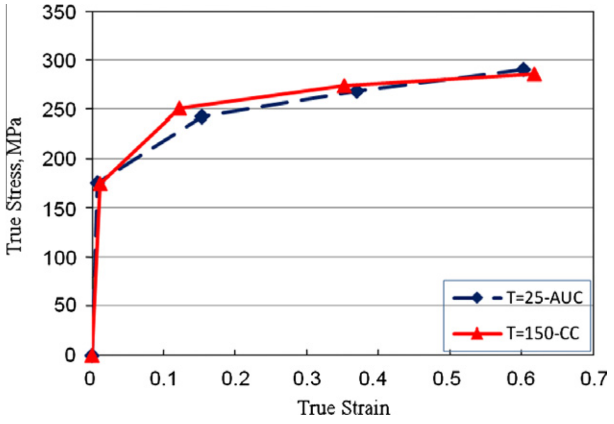


Fig. 8. The stress–strain curves in frictionless condition effect for CC at 150 °C and AUC at 25 °C.

Fig. 8 plots the stress–strain curves from extrapolated compression tests for AUC and high-temperature conventional compression (HCC). The true stress–strain curve for HCC at 150 °C is close to AUC's curve at 25 °C. The reduction in flow stress from increasing the temperature to 150 °C is comparable to the reduction caused by applying ultrasonic vibration. This result was in agreement with the literature [17], which indicated that the flow stress can be reduced when the temperature of the specimen was increased by pure heating, and also revealed that the specimen absorbed ultrasonic energy to cause the increased material temperatures and make a reduction in forming force. To clearly explore the effect of increased temperature, the temperature measurement tests were conducted.

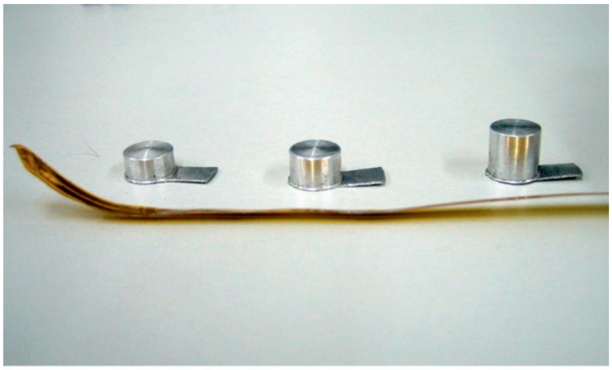
3. Temperature measurements during ultrasonic-vibration assisted upsetting

3.1. Experimental conditions

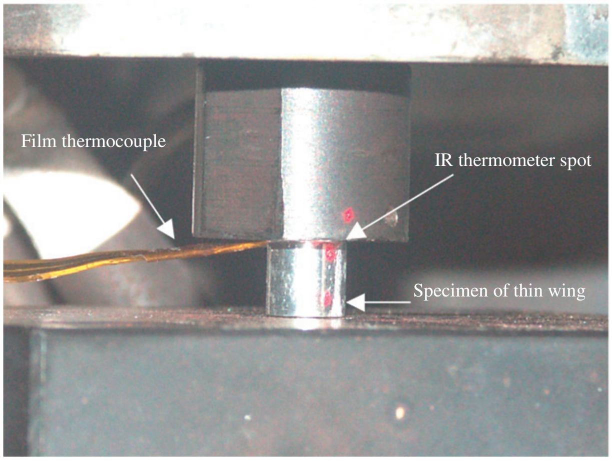
During compression tests, materials vibrate at high speeds. Inserting a thermocouple into specimens to measure temperature may not lead to accurate measurements because of damage to the thermocouple caused by the heat generated from vibrating materials. To overcome this issue, an IR thermometer (Raytek MX4) and a film-type thermocouple (ANRITSU ST-24 K) were used to obtain mean and indirect measurements of temperature during AUC tests. Specially designed specimens with thin (0.2 mm) wings were made to allow attachment of the film-type thermocouple (Fig. 9).

3.2. Experimental results

Fig. 10 shows the measured temperatures for the AUC tests for specimens with d_0/h_0 ratios of 2, 1.5, and 1. The results show that ultrasonic vibration increased the temperature of the materials. Smaller specimens had higher temperatures. This shows that the

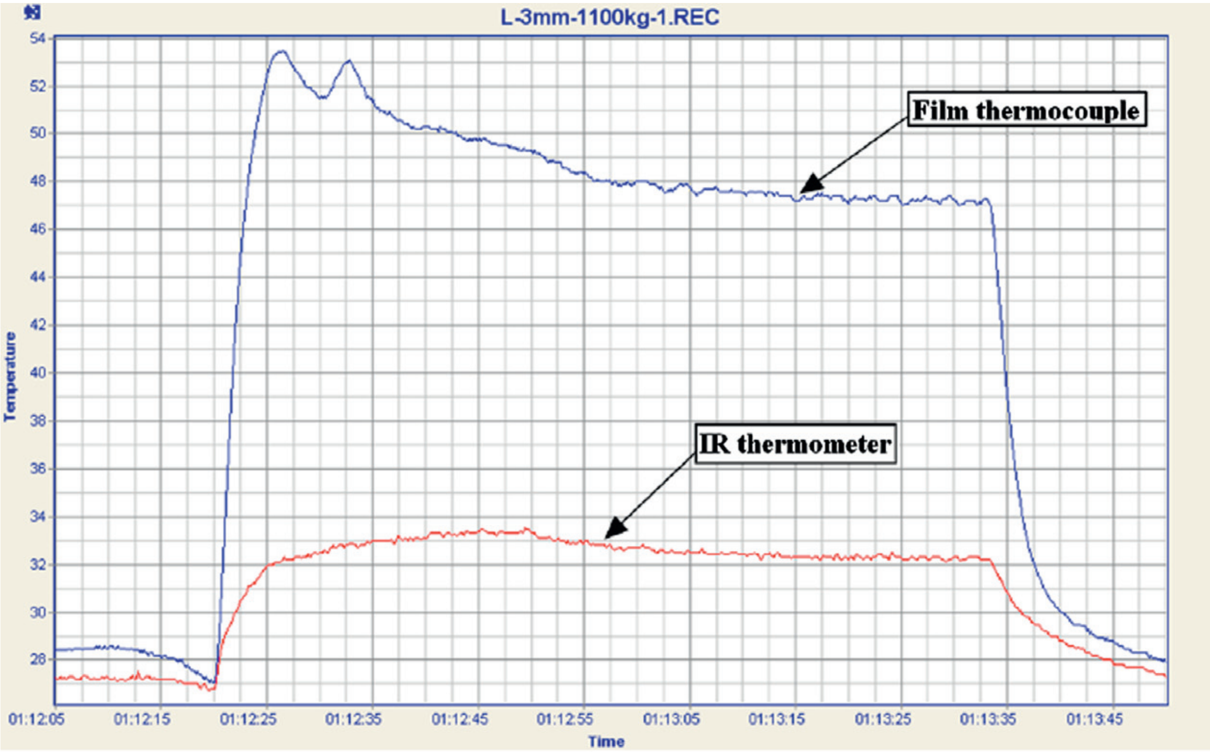


(a) Specimens with thin wings and film-type thermocouple.

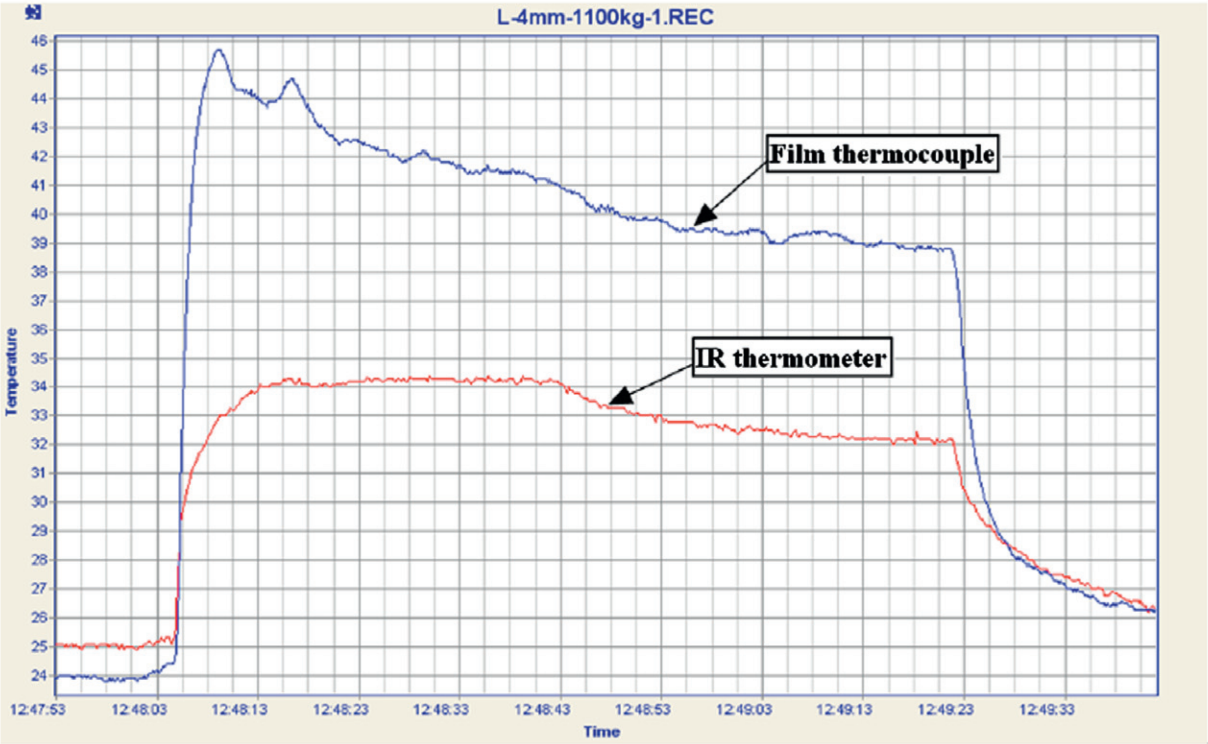


(b) Experimental setup of temperature measurements

Fig. 9. Temperature measurements in ultrasonic-vibration-assisted upsetting.



(a) Temperature measurement for $d_0 / h_0 = 2$ with 1100KgW compressive force

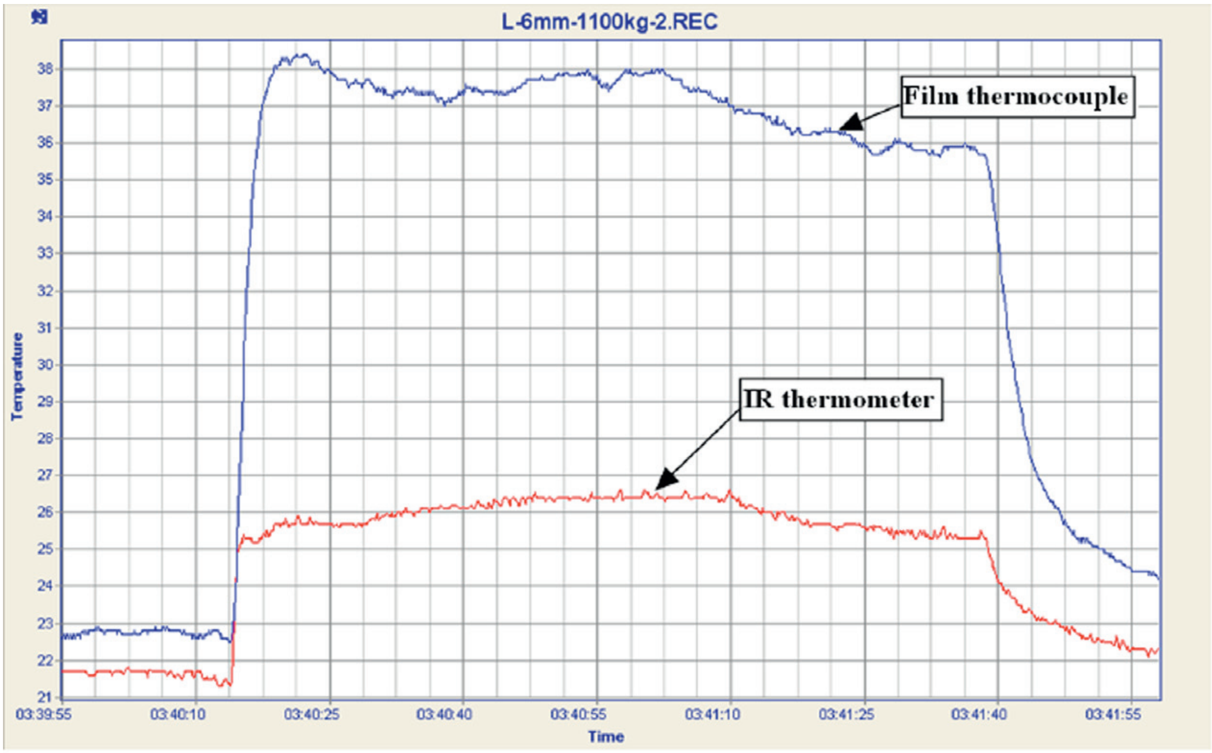


(b) Temperature measurement for $d_0 / h_0 = 1.5$ with 1100KgW compressive force

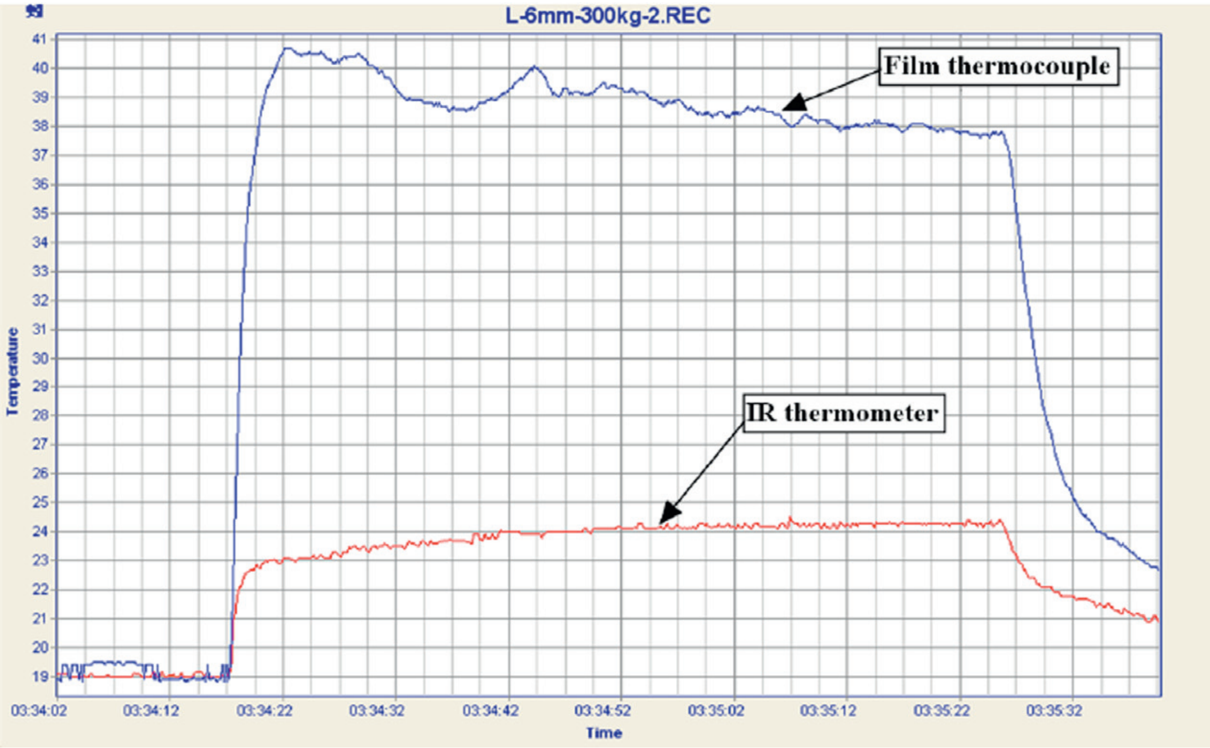
Fig. 10. Temperature measurements for AUC.

ability of ultrasonic vibration to increase temperature during upsetting is related to the size of the specimen. Smaller specimens absorb more ultrasonic energy per unit of volume, which results in higher temperatures.

Temperatures measured using the film-type thermocouple exceeded those measured with the IR thermometer. This was because the ultrasonic-vibration assisted upsetting caused ultrasonic welding. The temperatures of the specimens increased both through



(c) Temperature measurement for $d_0 / h_0 = 1$, with 1100KgW compressive force



(d) Temperature measurement for $d_0 / h_0 = 1$ with 300KgW compressive force

Fig. 10 (*continued*)

absorption of ultrasonic energy and through the rubbing that occurred between specimens and the die. Temperatures at the interface were therefore higher than the overall temperatures of the specimens. Furthermore, the IR thermometer measured only mean temperatures at focal spots with diameters of 6 mm. The film-type thermocouple measured temperatures around the thin wings, which was near the interface areas for the specimens. The temperatures were therefore higher than the values measured by

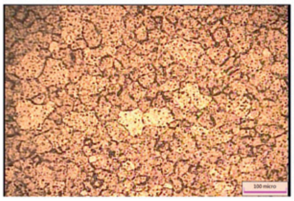
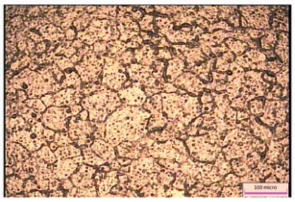
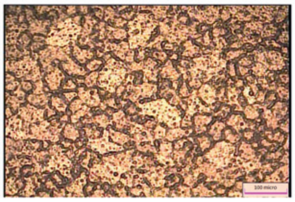
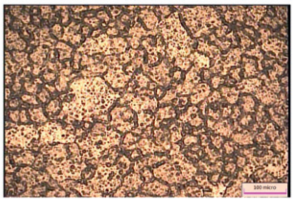
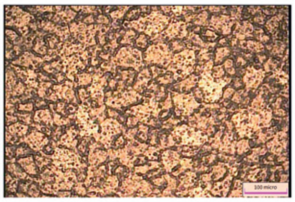
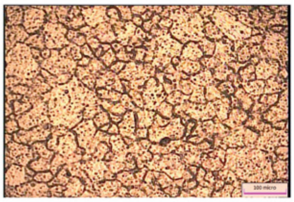
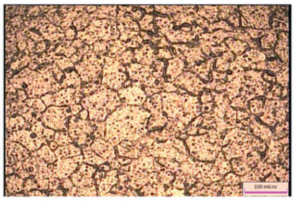
Compression Force	Conventional Compression	Axial Ultrasonic-vibration Compression
Before experiments		
500 kg		
800 kg		
1100 kg		
1500 kg		

Fig. 11. Comparison of specimens after CC and AUC tests.

the IR thermometer. This phenomenon was in agreement with Statnikov's research [15]. The high-frequency impact on the surface is accompanied by quick surface local heating. The generated thermal energy may not heat up the whole sample, but has a significant influence on the surface and improve the surface quality. Metal can absorb energy from the ultrasonic vibration through thermoelastic energy conversion [2,18], which could make a reduction in forming force.

Additionally, results show that temperatures increased rapidly during the initial vibration stages and then decreased with time. Fig. 10c and d shows that when $d_0/h_0 = 1$, the temperature of specimens under a compression load of 1100 kg was lower than that of specimens under 300 kg. This was because vibrating amplitude decreased as compression load increased, which reduced the output energy of the vibrations.

A discrepancy in temperature was found between indirectly measured temperatures (approximately 40–50 °C) and inferred temperatures (approximately 150–200 °C) from previous tests, which indicated that absorption of ultrasonic energy was not the only factor to increase the material temperatures. Other factors, such as stress superposition and dislocation activation, might also have been responsible. To clearly explore other mechanisms, metallographic analyses and micro-hardness tests were conducted.

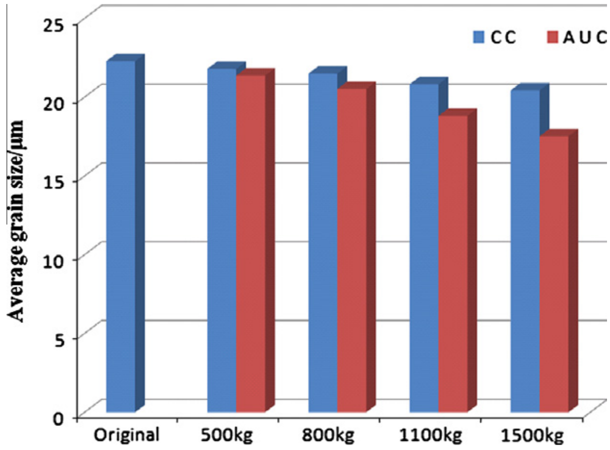


Fig. 12. Average grain sizes of specimens for CC and AUC.

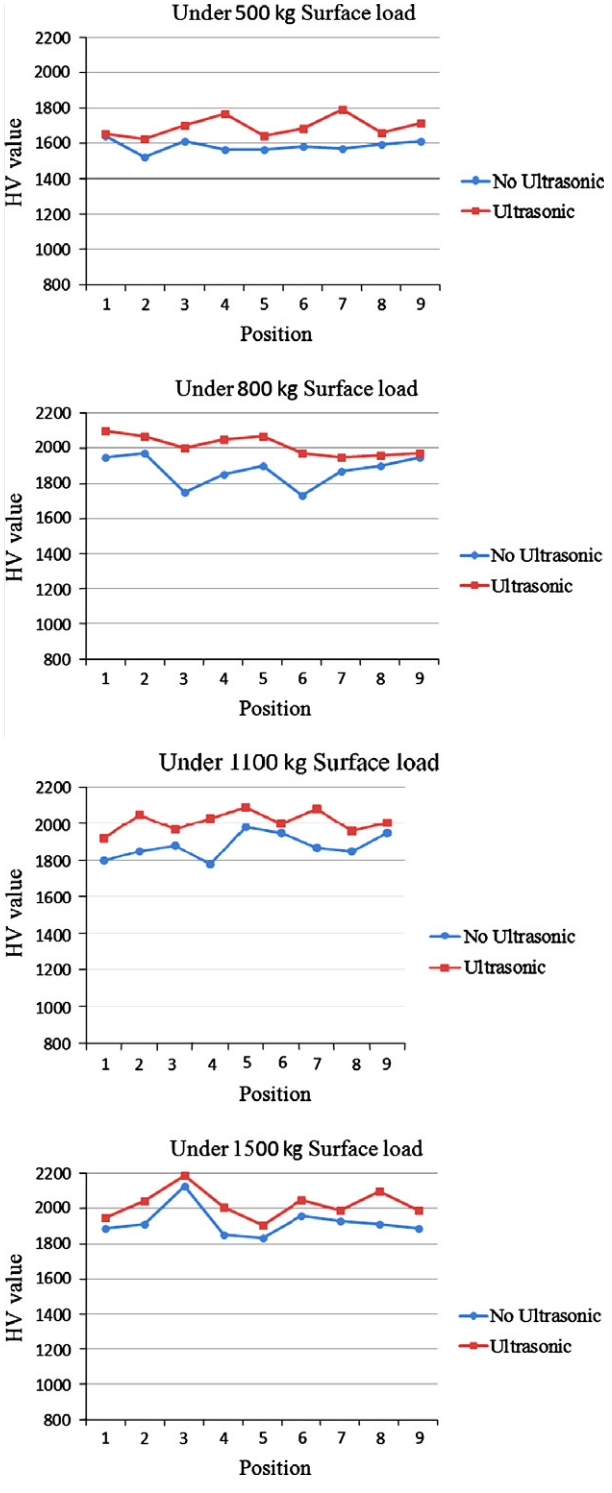


Fig. 13. Comparison of hardness in specimens after CC and AUC tests.

4. Metallographic analyses and micro-hardness tests

A number of recent studies have explored the effects of ultrasonic energy on the microstructures of materials, which revealed that applying ultrasonic energy refined the grain sizes in these materials therefore improving their mechanical properties [19–24]. Liu's research [24] indicated that the major approach to refine the grains of specimens for ultrasonic vibration is the motion of the dislocation.

To explore the effect of energy absorption of dislocation, metallographic analyses were conducted to investigate the grain size on specimen surface. A solution of hydrofluoric acid (10% hydrofluoric acid and 90% water) was used as an etchant. A surface area of one square inch was selected on each specimen for observation. These areas were magnified 100 times and shown on a microscope screen. Before the experiment, the grain size of the specimens was 22.285 μm. With CC, specimens were subjected to compression forces of 500, 800, 1100, and 1500 kg, which resulted in grain sizes of 21.795, 21.496, 20.820, and 20.433 μm, respectively. With AUC, specimens were subjected to compression forces of 500, 800, 1100, and 1500 kg, which resulted in grain sizes of 21.371, 20.523, 18.814, and 17.530 μm, respectively. When ultrasonic vibration was superimposed on specimens, the grains on their surfaces were refined (Figs. 11 and 12). The dislocation density increased during AUC, and these dislocations tangled together and the dislocation walls occurred. Finally, these dislocations walls changed into low or high angle grain boundaries, and then the original grains were refined into small grains and subgrains [3,24]. Specimen absorbed the energy from the motion of dislocation to soften the martial and make a reduction in forming force [4,25].

Micro-hardness tests were also conducted. Results showed that the forming process increased the specimens' surface strength because grains on the specimen surfaces were refined and the number of dislocation increased dramatically during ultrasonic-vibration superimposition (Fig. 13).

5. Conclusion

A series of experiments and analyses were conducted to explore and further understand the effects of ultrasonic vibration for the mechanical properties and microstructure changes of materials during ultrasonic-vibration assisted A6061-T6 aluminum alloy upsetting, and three mechanisms including the interface friction effect, the increased temperatures, and energy absorption of dislocation were clearly identified and analyzed.

The results of the extrapolated compression experiment showed that when friction is negligible, ultrasonic vibration can still effectively reduce material flow stress. Temperature measurement tests showed that metal can absorb energy from the ultrasonic vibration through thermoelastic energy conversion, which could make a reduction in forming force; however, heat energy was not the only factor. Furthermore, the results of metallographic analyses and micro-hardness tests indicated that energy absorption of dislocation was also occurred, which make a reduction in forming forces during upsetting.

Because of current limitations in measuring apparatuses, direct measurements of interface temperature could not be achieved. Instead of using real temperature measurements at the interface, this study relied on indirect and average local temperature measurements to understand the thermal effects of ultrasonic vibration. A more precise measuring method should be used in the future to accurately explore the relationship between ultrasonic vibration and temperature increase in specimens. Further investigation on the effects of the superposition of stress will be conducted to develop the full mechanisms of ultrasonic vibration upsetting.

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