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The influence of ultrasonic-vibration on hot upsetting of aluminum alloy

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Abstract

The traditional ultrasonic apparatus cannot be operated at high temperature, explaining why the effect of ultrasonic-vibration on high temperature metal forming has seldom been addressed in literature. This study establishes an ultrasonic-vibration hot upsetting system. A cooling mechanism is used to solve the problem of high temperature. The effects of temperature and strain rate during ultrasonic-vibration on the upsetting of aluminum alloy were explored using this new system. Experimental results indicate that ultrasonic-vibration can considerably reduces the compressive forces during hot upsetting. The reducing effect on compressive forces decreases while the temperature increases. The strain rate does not significantly affect the reducing effect on compressive forces.

Keywords: Ultrasonic-vibration; Hot upsetting; Aluminum alloy

1. Introduction

Many new materials, such as titanium alloys, magnesium alloys and inter-metallic compounds, are difficult to produce. Production depends on the development of new processes to overcome the difficulties that arise during the metal forming process. The technique of ultrasonic-vibration has been applied widely in metal forming. The difference between conventional metal forming and the ultrasonic-vibration metal forming is that the latter exploits ultrasonic energy to act on the die and then uses the die to deform the work-piece.

Some interesting effects arise in the application of ultrasonic-vibration for metal forming processes, such as the reduction of the friction between the die and the work-piece, the reduction of the forming forces, and decreases of the spring-back angle during sheet metal forming. These effects increase the forming limit of materials. Blaha and Langenecker were the first to investigate the use of ultrasonic-vibration in relation to plasticity of metals [1,2]. They superimposed high-frequency vibrations onto the static load during the tensile testing of a zinc single crystal specimen. In the experiment, they observed a substantial reduction in the yield stress and the reduction of the flow stress. This phenomenon is the so-called Blaha effect. Kempe [3] proposed three mechanisms by which dislocations may absorb energy from vibrations; they are (1) a resonance mechanism, (2) a relaxation mechanism, and (3) a mechanism of simple hysteresis. Nevill [4] attributed the reduction of the flow stress to the superposition of steady stress and the alternation of stress, and proposed the stress superposition mechanism.

Lehfeldt and Pohlman [5] examined the feasibility of exciting a ball by vibration on a revolving plate in experiments on the influence of the ultrasonic-vibration on friction. The frictional forces are minimal at the contact surface when the direction of vibration is parallel to the direction of motion. Jimma et al. [6] applied ultrasonic-vibration to the deep drawing process and show that

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ultrasonic-vibration deep drawing is very effective in increasing the limiting drawing ratio (LDR) and surpassed the theoretical value LDR of deep drawing by ideal tools without friction. Murakawa et al. [7,8] investigated the effects of radial ultrasonic-vibration drawing (RVD) and axial ultrasonic-vibration drawing (AVD), and compared them to those of conventional wire drawing (CD). It was proven to be highly effective in increasing the critical drawing speed by ultrasonic wire drawing, and the RVD operation appears to be more productive than the AVD operation.

Huang et al. [9] investigated the benefits of applying the axial ultrasonic-vibration of forming tools in an upsetting process; he used plasticine as a model material to simulate the hot metal. According to that study, applying an ultrasonic-vibration to the die reduces the mean forming force during upsetting. He concluded that the stress superposition effect and the reduction of interface friction contributed to the above phenomenon.

Conventional ultrasonic apparatus cannot be operated at high temperatures, so relatively few investigations have addressed the effect of ultrasonic-vibration metal forming at high temperature. This study, establishes an ultrasonic-vibration hot upsetting apparatus to overcome this difficulty. The effects of temperature and strain rate during ultrasonic-vibration on the hot upsetting of aluminum alloy are investigated using this apparatus.

Fig. 1. Ultrasonic hot upsetting experiment set up.

2. Ultrasonic-vibration hot upsetting apparatus

2.1. Hot upsetting machine

Hot upsetting is based on a process of unconfined uni-axial deformation of a cylindrical specimen between parallel rigid platens. In this study, an especially designed microcomputer server controls the hot upsetting machine. The machine has four conducting pillars and a server motor to control the velocity of the platens. The maximum loading capacity is 2000 kg W; resolution of the force is 10 N; the resolution of displacement is 0.005 mm and the range of velocity is 0.5–50 mm/min. Fig. 1 shows this machine.

2.2. Heating and cooling system

Materials are easily oxidized at high temperature, so the heating system is enclosed in a vacuum chamber, which can sustain a maximum temperature of 600 °C and vacuum pressure of 10^{-3} Torr. The system was designed with a free moveable die and a vacuum furnace and so was ideal for performing experiments at a high temperature in a vacuum.

During the ultrasonic-vibration hot upsetting experiment, heat may be transferred to the mechanical apparatus affecting the parts. The vacuum furnace and the both upper and lower dies also require a cooling system to prevent damage to the part. The heating of the dies proceeds mainly by thermal radiation, so the rate of heating was lower than the rate of liquid cooling. An auxiliary heating system was designed on both the upper and lower dies to make compensate for the heat to increase the accuracy of the temperature control. Three independent PID controlled are used to control the temperature. This temperature compensation can maintains the temperature between the dies and the inner furnace within ±1 °C.

2.3. Ultrasonic-vibration system

The ultrasonic-vibration system includes an ultrasonic frequency generator, a piezoceramic vibration transducer, a resonator and an ultrasonic forming die. The ultrasonic frequency generator has a maximum capacity of 2 kW and provides power for a piezoelectric transducer to generate ultrasonic-vibration. This generator includes an automatic frequency-tracking controller, which is able to maintain the system resonant frequency at 20 kHz ± 300 Hz. A booster then amplifies the amplitude of vibration and transmits it to a horn. The ultrasonic-vibration system was fixed by flange located at the booster's vibration node. The step horn, which is resonant in a longitudinal mode, was uniquely designed for use in upsetting. In this investigation, finite element simulations software, ABAQUS, was used to determine the dimensions of this stainless steel horn. The results of the tests showed that the simulated and experimental resonant frequencies were very close to each other.

3. Ultrasonic-vibration hot upsetting experiment

3.1. Experimental procedure

The ultrasonic-vibration hot upsetting experiment proceeded as follows. First, the ultrasonic-vibration system and vacuum furnace were set up on a hot bench controlled by a microcomputer server. Second, the specimen was placed between parallel dies. Then, a 20 kg W preload was applied to the specimen. The heating controller was turned on. When the temperature reached the designated temperature, it was hold constant for 10 min before the rest of the experiment was performed. Whenever the loading reached 70 kg W during an experiment, the ultrasonic-vibration was superimposed.

3.2. Experimental conditions

Table 1 shows material properties and the hot upsetting conditions used in the experiment. The specimens used in this study were aluminum alloy A6061 that was 6 mm high and 6 mm in diameter. The compression displacement was set to 4 mm (equivalent to a 66.7% compression ratio), and the true strain rate was controlled throughout the experiment. The tests were performed under dry conditions without lubricant. During ultrasonic-vibration hot upsetting, the axial vibration frequency was 20 kHz. The amplitude was set to 5.6 μm.

4. Experimental results and discussion

4.1. Effects of ultrasonic-vibration and temperature on upsetting

Fig. 2 shows the experimental results of load–displacement curves for the conventional upsetting (CU) and axial ultrasonic-vibration upsetting (AUU). The temperature was set to 25 °C and the true strain rate was 0.03 1/s. Fig. 2(a) shows that for CU, the compression ratio was 67% (with a displacement of 4 mm) under a compressive forces 1511 kg W for CU, but for AUU, a compressive forces was 1296 kg W was required to yield the same compression ratio. The compressive force was therefore 215 kg W lower for AUU. These results indicate that ultrasonic-vibration effectively reduces the material flow stress. Fig. 2(b) shows reduced compressive forces–displacement curves. Under ultrasonic-vibration, increasing the compression ratio increases the reduction in the compressive forces. Restated, ultrasonic-vibration strengthens the effect of the reduced compressive forces when the compressing ratio is increased.

Figs. 3–5 show the load–displacements curves of the CU and AUU, with a constant true strain rate of 0.03 1/s at temperatures set to 100 °C, 200 °C and 250 °C, respectively. At all tested temperatures, the load decreased when the ultrasonic-vibration was applied.

Fig. 6(a) and (b) plot the relationship between temperature and ultrasonic-vibration. When the compression

Table 1
Material and hot upsetting conditions

Specimen material	Aluminum alloy (A 6061)
Tooling material	Stainless steel (SUS304)
Size of specimen	$\phi 6.0 \times 6.0$ mm
Lubricant	N/A
Reduction (R)	66.7%
True strain rate ($\dot{\varepsilon}$)	0.003 1/s, 0.03 1/s
Temperature of specimen	25 °C, 100 °C, 200 °C, 250 °C

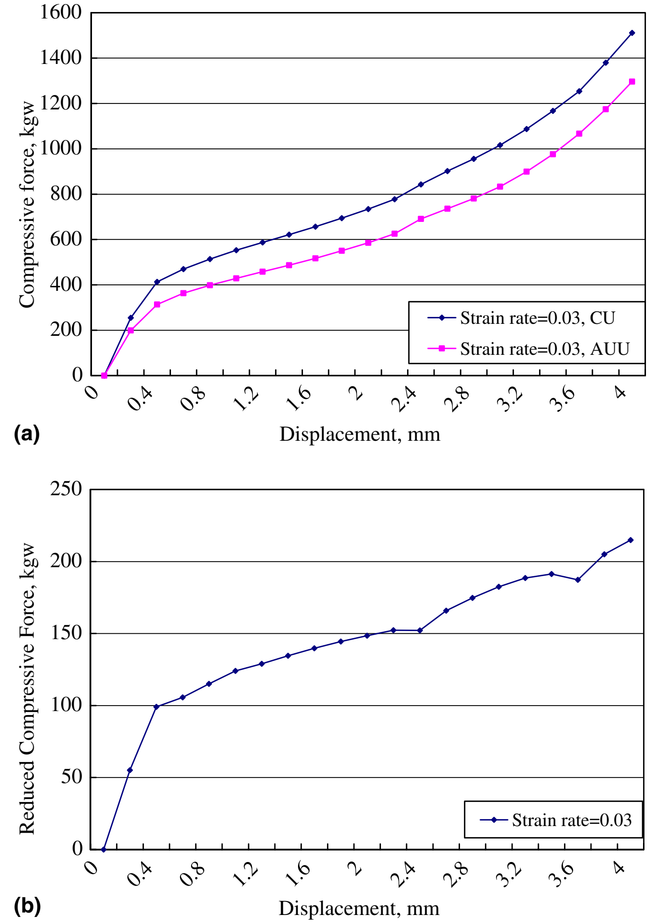

Fig. 2. Load–displacement curves for CU and AUU at 25 °C: (a) compressive forces–displacement curves for CU and AUU; (b) reduced compressive forces–displacement curves.

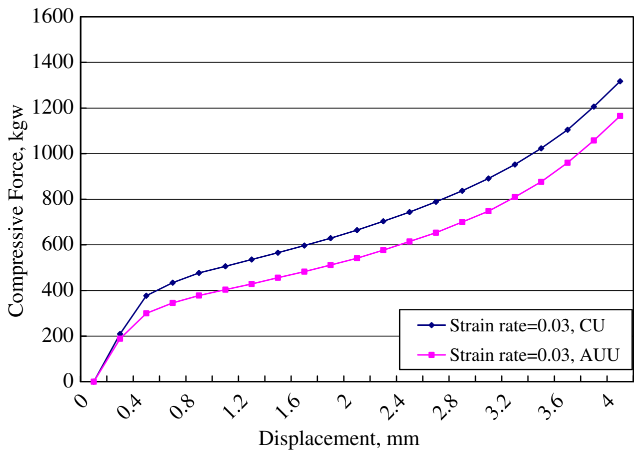

Fig. 3. Load–displacement curves for CU and AUU at 100 °C.

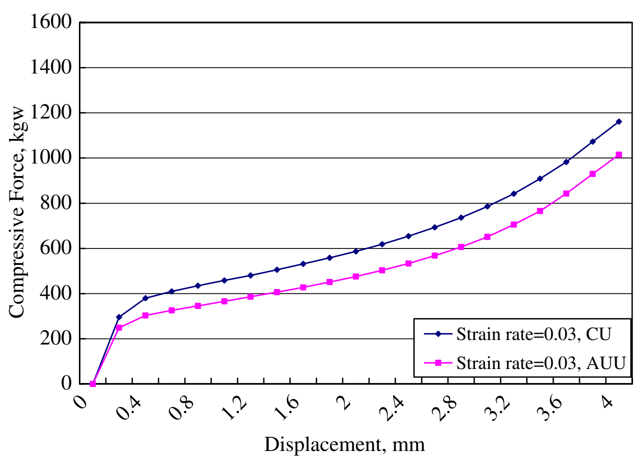

Fig. 4. Load–displacement curves for CU and AUU at 200 °C.

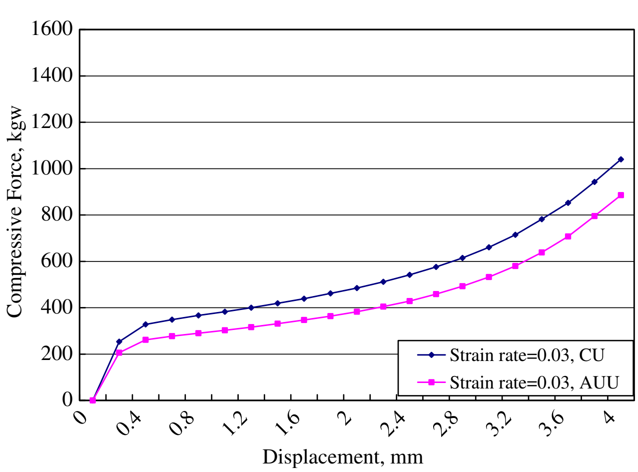

Fig. 5. Load–displacement curves for CU and AUU at 250 °C.

displacement was 4 mm the compressive forces of AUU at 25 °C and 100 °C were very close to those of CU at 100 °C and 200 °C. Accordingly, the reduction in flow stress caused by increasing the temperature by 100 °C is comparable to that caused by applying ultrasonic-

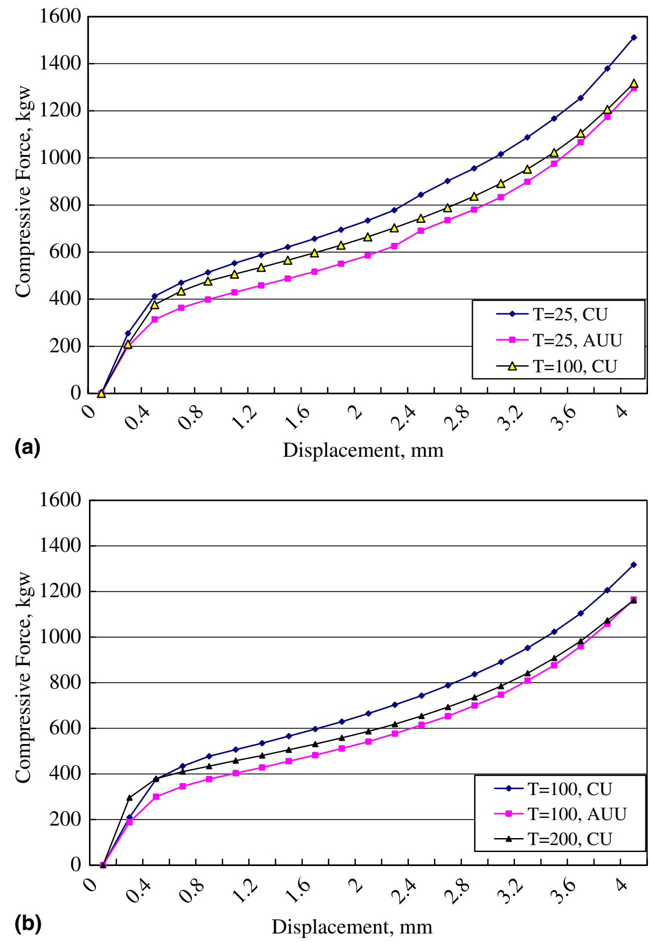

Fig. 6. Relationship between temperature and ultrasonic-vibration in CU and AUU: (a) load–displacement curves of CU at 25 °C and 100 °C, AUU at 25 °C; (b) load–displacement curves of CU at 100 °C and 200 °C, AUU at 100 °C.

vibration. However, when the compression displacement was less than 3 mm, the effect of ultrasonic-vibration exceeded than that of increasing the temperature by 100 °C.

Fig. 7(a) and (b) indicate that the increase in temperature reduced compressive forces for CU and AUU at a true strain rate of 0.03 1/s. Fig. 7(c) plots the load–displacement curve of the compressive forces reduced by ultrasonic-vibration at various temperatures. The reduction in compressive forces caused by ultrasonic-vibration was distinguished at 25 °C. The magnitude of the compressive forces reduction caused by ultrasonic-vibration decreases as the temperature is increased.

4.2. Effects of ultrasonic-vibration and strain rate on upsetting

In this part, the true strain rate was set to 0.03 1/s and 0.003 1/s in CU and AUU, respectively, at temperatures from 25 °C to 250 °C. Fig. 8 shows that the strain rate did not influence CU and AUU at 25 °C. In Fig. 9, when

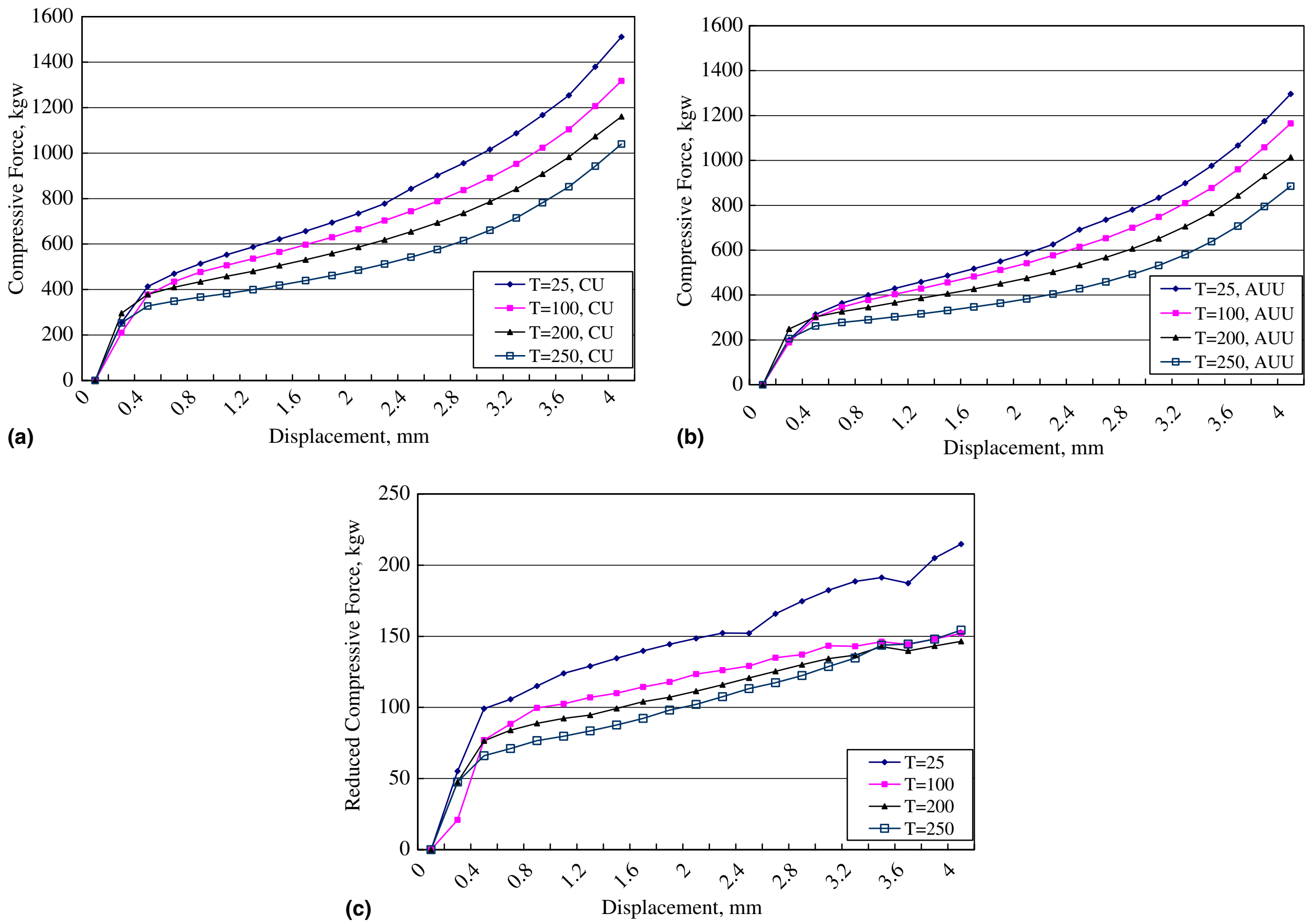

Fig. 7. Experimental results for CU and AUU at 25 °C, 100 °C, 200 °C and 250 °C: (a) load–displacement curves of CU at 25 °C, 100 °C, 200 °C and 250 °C; (b) load–displacement curves of AUU at 25 °C, 100 °C, 200 °C and 250 °C; (c) reduced force-displacement curves for AUU at 25 °C, 100 °C, 200 °C and 250 °C.

the temperature was increased to 250 °C, the loading force of CU and AUU decreased as the strain rate was lowered to 0.003 1/s. These results indicated that, at high temperature, the strain rate markedly affected the material's flow stress, regardless of whether ultrasonic-vibration was applied.

Fig. 10 shows the differences of compressive forces vs. displacements of CU at true strain rates of 0.03 1/s and 0.003 1/s. The difference of compressive forces (F_d) is defined as

$$F_d = F_{\dot{\varepsilon}=0.03} - F_{\dot{\varepsilon}=0.003} \quad (1)$$

where $F_{\dot{\varepsilon}=0.03}$ is the loading associated with a strain rate of 0.03 1/s and $F_{\dot{\varepsilon}=0.003}$ is the loading associated with a strain rate of 0.003 1/s.

Fig. 11 plots the differences of compressive forces vs. displacements of AUU at strain rates of 0.03 1/s and 0.003 1/s. At 250 °C for both CU and AUU, the strain rate significantly affects the compressive forces. Furthermore, when the displacement exceeded 3 mm in 25 °C and 100 °C, the difference of compressive forces becomes negative because the ultrasonic-vibration operation proceeds for a long time, increasing the system's temperature, reducing the efficiency of the power transformation of the system.

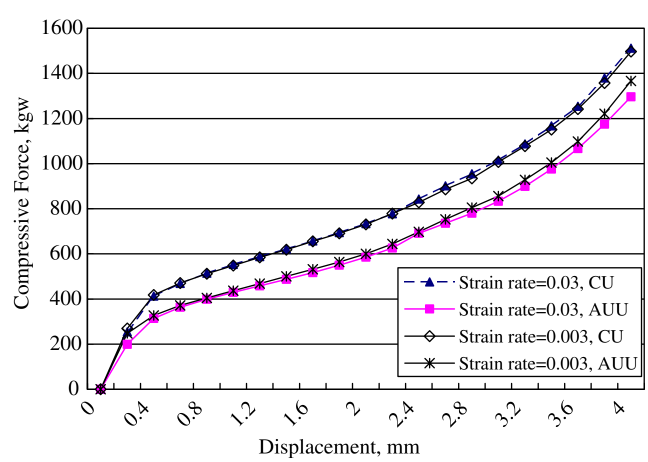

Fig. 8. Load–displacement curves for CU and AUU at 25 °C; the strain rate was 0.03 1/s and 0.003 1/s.

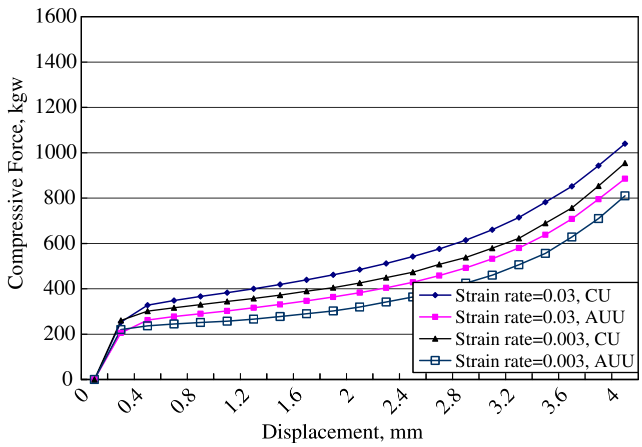

Fig. 9. Load–displacement curves for CU and AUU at 250 °C; the strain rate was 0.03 1/s and 0.003 1/s.

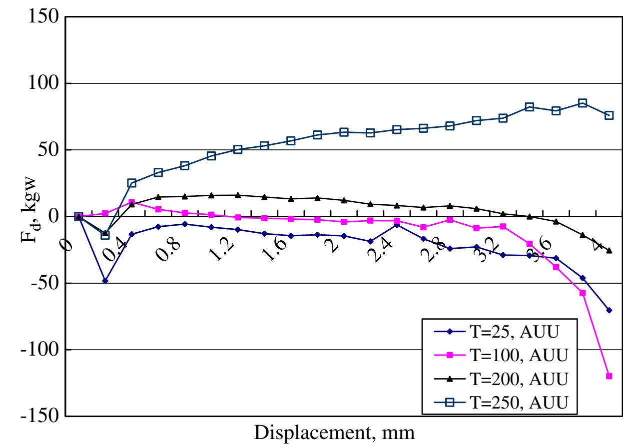

Fig. 11. Differences of compressive forces vs. displacements of AUU in strain rate of 0.03 1/s and 0.003 1/s.

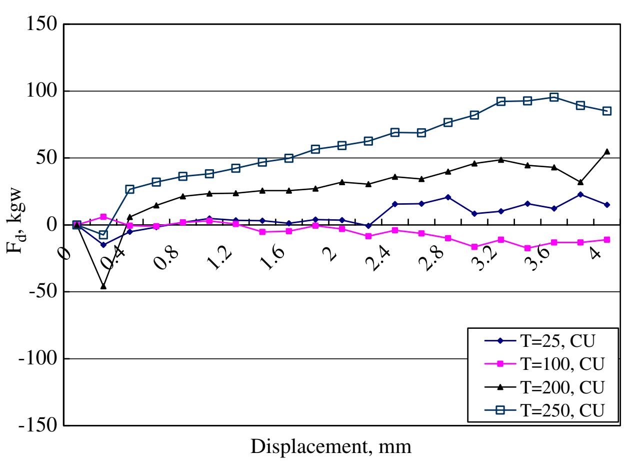

Fig. 10. Differences of compressive forces vs. displacements of CU in strain rate of 0.03 1/s and 0.003 1/s.

4.3. Mechanisms of ultrasonic-vibration in upsetting

Several investigations have demonstrated that the mechanisms of ultrasonic-vibration in metal forming are as follows: (1) reduction of flow stress; (2) reduction of the friction between die and work-piece, and (3) increase of the temperature between die and work-piece. The most common causes of the reductions of flow stress are as follows: (1) dislocations might absorb energy through resonance and overcome slip obstacles; (2) dislocations are able to absorb energy from an applied periodic stress and overcome the energy barrier; (3) the internal friction effect; and (4) the superposition of steady stress and alternating stress. Overall, the effects of ultrasonic-vibration on metal forming are very complex. Apart from the reduction of flow stress, the friction between die and work-piece and the raised temperature of the material must also be considered. For example, the friction effect is stronger when drawing or deep drawing is performed [6–8].

This study addresses the effect of ultrasonic-vibration on hot upsetting. During the experiments, the ultrasonic-vibration frequency was 20 MHz, which is far from the ordinary natural frequency, 100 MHz, of a dislocation loop [10]; therefore, dislocations would absorb little energy of vibration due to the lack of resonance. Accordingly, dislocations would not make much effect on flow stress reduction. However, as shown in Fig. 2(b), during ultrasonic-vibration, the effect of compressive forces reduction was increased with the increase in the compression ratio. If the reduction of flow stress caused by ultrasonic-vibration was attributed only to the superposition of steady stress and alternating stress, then the compressive forces reduction must be a constant. Therefore, mechanisms other than the superposition of stresses should also be considered.

Fig. 7(c) shows that the magnitude of the reduction in force caused by ultrasonic-vibration decreases as the temperature is increased. The causes may be as follows: (1) The material's creep characteristic will gradually come to dominate at high temperature. The deformation mechanism therefore differs from that at room temperature. The ultrasonic-vibration energy absorbed by the material is reduced, weakening the effect of ultrasonic-vibration. (2) Ultrasonic-vibration increases the interface temperature between die and work-piece, and reduces the effect of the reduction in friction.

The experimental results indicate that the strain rate does not further reduce the material flow stress associated with ultrasonic-vibration. Currently, the developed ultrasonic-vibration system is limited to a relatively short operation time; only two strain rates were used during experiments; therefore, the connection between ultrasonic-vibration and strain rate effect has not been well explored. A detailed study will be required in the future.

5. Conclusions

This study established the ultrasonic-vibration hot upsetting system. By adopting a cooling mechanism, the system overcomes high temperature operation difficulty. The effects of temperature and strain rate during the ultrasonic-vibration upsetting of the aluminum alloy were investigated. Based on the results of this study, we conclude the following:

(1) During the hot upsetting process, the difference between the temperatures of the furnace and the work-piece was significant. Therefore, a device to heat the die was required to eliminate the difference between the temperature of die and the work-piece.
(2) An axial ultrasonic-vibration can reduce the deformation resistance in hot upsetting.
(3) The effect of ultrasonic-vibration on hot upsetting cannot be explained by a simple mechanism, such as the effect of interface friction, or superposition of stress, or the absorption by dislocations of the ultrasonic-vibration energy.
(4) The magnitude of the reduction of forming stress in ultrasonic-vibration hot upsetting decreases as the temperature increases.
(5) The strain rate does not markedly affect the reduction of the flow stress in ultrasonic-vibration hot upsetting.

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