Rare Metal Materials and Engineering
Volume 51, Issue 4, April 2022
Available online at www.rmme.ac.cn

Science Press

Cite this article as: Gao Tiejun, Wang Xu, Yang Yong, et al. Effect of Compound Energy-Field with Temperature and Ultrasonic Vibration on Bending Properties of 2195 Al-Li Alloy[J]. Rare Metal Materials and Engineering, 2022, 51(04): 1226-1230.

ARTICLE

Effect of Compound Energy-Field with Temperature and Ultrasonic Vibration on Bending Properties of 2195 Al-Li Alloy

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Abstract: In order to solve the problem of fracture and large springback during the bending forming of Al-Li alloy, the bending forming process under the compound energy-field (CEF) of temperature and ultrasonic vibration was studied. It is expected to reduce the temperature required for bending forming of Al-Li alloy with the help of ultrasonic vibration energy-field while maintaining the forming quality. The research was carried out by combining with ultrasonic vibration energy of 1.0~1.6 kW under the temperature conditions of 80~200 °C. The effects of CEF on the bending force, springback, bending fillet radius and microstructure of 2195 Al-Li alloy sheets were analyzed. The results show that at a relatively low temperature for hot forming, the bending force can be reduced by combining with ultrasonic vibration energy-field. The springback and fracture are effectively inhibited, thus improving the high temperature softening effect and bending properties of 2195 Al-Li alloy.

Key words: 2195 Al-Li alloy; temperature and ultrasonic vibration; compound energy-field; bending properties; microstructure

Adding lithium to the aluminium alloy can make the aluminium alloy have lower density, higher elastic modulus, better corrosion resistance and better low-temperature performance. Therefore, Al-Li alloys are widely used in the new-generation aircraft and have broad application prospects in the aerospace field[1-4]. For example, Al-Li alloys have been used to manufacture fuel tanks, frames, wing skins and other components in Boeing 747 and 777 passenger aircraft, which can reduce weight by 14.6% and flight cost by 2.2%. Moreover, the fuselage, long stringers, ailerons and skins of the C919 passenger aircraft use a large number of third-generation Al-Li alloys, with a total weight reduction of 7%[5,6].

However, due to the poor plasticity of Al-Li alloys at room temperature, it is difficult to produce complex parts by the traditional cold forming processes. At present, thermoforming is the primary forming method for manufacturing complex parts[7-12]. It takes advantage of the thermal effect of material to improve the formability of Al-Li alloys and the quality of the formed parts. Ma [13] and Yang[14] found that the forming limit and formability of 5A90 Al-Li alloy can be improved by the increase of forming temperature. Fan[15] adopted an integrated process of hot deformation-cold die quenching to form U-shaped specimen of 2195 Al-Li alloy, and found that the springback of the specimen is inhibited.

Besides, the formability of Al-Li alloys and the quality of the formed parts can also be improved by changing the stress state of the specimen. For example, in recent years, the ultrasonic vibration-assisted forming process has been studied. It takes advantage of volume effect and surface effect to change the internal stress state and friction state between die and specimen. Langenecker et al[16] carried out the ultrasonic vibration-assisted tensile experiments using the single-crystal Zinc. The results showed that the softening effect is induced by the ultrasonic vibration, which is similar to the thermal softening due to high temperature. Gao et al[17] studied the effects of ultrasonic vibration on the mechanical properties of TA2 titanium alloy sheets and the friction coefficient between the contact surfaces. The results showed that the ultrasonic

Received date: April 07, 2021
Foundation item: National Natural Science Foundation of China (52075347, 51575364)
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vibration can effectively improve the forming limit of the TA2 titanium alloy sheets. Pasierb et al[18] performed ultrasonic vibration-assisted deep drawing experiments and found that the drawing force decreases and the dimensional accuracy is improved when the ultrasonic vibration is applied.

The compound effect of temperature field and ultrasonic vibration can further improve the formability of material and the quality of the formed parts. Hung et al[19] indicated that ultrasonic vibration can considerably reduce the compressive force of A6061 aluminium alloy during hot upsetting. And the force reduction decreases when the temperature increases. Gao et al[20] found that the compound energy-field of temperature and ultrasonic vibration can further reduce the flow stress and yield strength of the TC4 titanium alloy sheet and improve the formability under thermal conditions.

1 Problem and Solution

1.1 Problem statement

2195 Al-Li alloy, the third-generation high strength Al-Li alloy, is mainly used in cryogenic propellant tanks and liquid oxygen tanks of launch vehicles, as well as the beams, frames, webs and other structural parts of aircraft. The chemical composition and mechanical properties of 2195 Al-Li alloy are shown in Table 1 and Table 2, respectively. Due to the poor plasticity, when the maximum bending angle reaches 47.5° in 90° V-bending experiments at room temperature (the specimen size was 20 mm×50 mm and the thickness was 1.5 mm), fracture will occur in the center of the outer layer of the bending part as shown in Fig. 1. However, when the bending angle is less than 47.5° , the bending parts have a large springback. It is difficult to achieve the ideal forming results. In terms of energy-saving and emission reduction, forming quality and machining efficiency, the forming method of compound energy-field (CEF) with temperature and ultrasonic vibration was proposed.

1.2 Experimental device and scheme

Considering the application of CEF, the experimental device is shown in Fig.2. It consists of an ultrasonic vibration-assisted bending device (including bending die, ultrasonic generator and ultrasonic amplitude amplifier pole), a temperature control system and a water-cooling circulation system. The bending punch was connected with the moving beam of the testing machine. The lower die was connected with the ultrasonic amplitude amplifier pole and fixed on the workbench. In the experiment, the specimen was heated by the temperature control system. After the temperature of the experimental environment reached the target value and was maintained for 5 min, the bending experiment was started. During the bending process, the bending force was monitored by the force sensor. The experiment was carried out at 80, 100, 140, 170 and 200 °C with a constant bending speed of 1 mm/min. The ultrasonic vibration frequency was 20 kHz, and the ultrasonic vibration power was 1.0, 1.2, 1.4, and 1.6 kW.

Table 1 Chemical composition of 2195 Al-Li alloy sheet (wt%)

Cu	Mg	Ag	Zn	Mn	Li	Al
3.91	0.40	0.52	≤0.25	≤0.25	1.01	Bal.

Table 2 Mechanical properties of 2195 Al-Li alloy sheet at room temperature

Yield strength/MPa	Tensile strength/MPa	Elongation/%
471.4	531.3	15.8

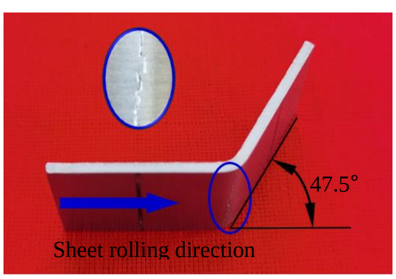

Fig.1 Bending fracture specimen of 2195 Al-Li alloy

2 Results and Discussion

2.1 Effect of the CEF on bending force

Fig.3 shows the bending force-punch stroke curves of 2195 Al-Li alloy sheets under the CEF. At the temperature of 80 °C, the fracture occurs when the punch stroke reaches 6.3 mm under the single temperature field. However, the fracture does not occur until the punch stroke reaches 8.2 mm under the CEF. It indicates that the bending properties of 2195 Al-Li alloy bending parts are improved under the CEF (Fig.3a). In the temperature range of 100~200 °C, when the stroke of the bending punch reaches 9.6 mm, the bending force increases rapidly. Thus the specimen has fitted the die at this time. It can be seen that compared with the single temperature field, the bending force of 2195 Al-Li alloy decreases obviously and fluctuates wildly, which reflects the effect of ultrasonic vibration stress superposition on the 2195 Al-Li alloy specimen. There are two main reasons for the reduction of the bending force. On the one hand, the input of ultrasonic vibration energy will increase the activating energy of the material and reduce the strength of the material. On the other

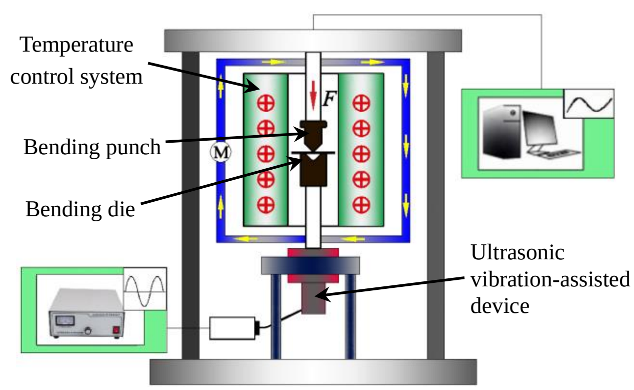

Fig.2 Experimental device of compound energy-field with temperature and ultrasonic vibration-assisted bending

hand, the instantaneous separation between the specimen and die due to the surface effect of ultrasonic vibration changes the friction state. And it can be seen from Fig.3 that under the same thermal condition, the reduction of bending force increases when the ultrasonic vibration power increases.

2.2 Effect of the CEF on springback of bending parts

Fig. 4 shows the bending specimens of 2195 Al-Li alloy under the CEF. Fig. 5 shows the springback angle under different conditions. The springback angle of the specimen is 14.6° under the single temperature field at 100 °C. When the ultrasonic vibration power is 1.0, 1.2, 1.4 and 1.6 kW, the springback angle is 13.3°, 12.1°, 11.0° and 10.4°, and the reduction is 8.90%, 17.12%, 24.66% and 28.77%, respectively. It shows that the ultrasonic vibration energy input can increase the effect on inhibiting springback of the bending part. It can be seen from Fig. 5 that under the same ultrasonic vibration energy condition, the springback angle of 2195 Al-Li alloy sheet decreases with increasing the temperature. But compared with low temperature, the effect of high temperature tends to weaken. This is consistent with the research results of Hung et al[19].

Based on the effects of temperature and ultrasonic vibration on the springback of 2195 Al-Li alloy bending parts, it can be seen that the effect of CEF is equivalent to the effect of high single temperature field. For example, the effect of inhibiting springback of the 2195 Al-Li alloy under CEF with 100 °C/1.0 kW is consistent with that under the single temperature field at 140 °C. Moreover, the effect of inhibiting springback of the 2195 Al-Li alloy under CEF with 100 °C/1.4 kW is consistent with that under the single temperature field at 200 °C. Therefore, when the temperature field is combined with the ultrasonic vibration energy-field at a lower temperature, it can be equivalent to the single temperature field at a higher temperature. So the forming temperature can be effectively decreased.

2.3 Effect of the CEF on fillet radius of bending parts

Fig. 6 shows the bending fillet radius of 2195 Al-Li alloy under the CEF. It can be seen that the bending fillet radius decreases under the CEF. And the larger ultrasonic vibration power can better reduce the bending fillet radius and improve the quality of the formed parts. However, compared with the effect of CEF on the springback of bending parts, the effect on the bending fillet radius variation is small. The reason is that the punch stroke mainly controls the bending process. When the punch stroke reaches 9.6 mm, the bending force increases rapidly, indicating that the specimen has fitted the die. Under this condition, the geometric shape of the specimen before springback is basically the same, but the fillet radius of the specimen is changed due to different springback angles after bending. Generally, a large springback angle will result in a large fillet radius.

2.4 Effect of CEF on microstructure of bending parts

The above research results show that the problem of fracture and large springback of 2195 Al-Li alloy bending parts can be solved at a lower temperature under the CEF. Moreover, in order to study the effect of CEF on the microstructure of 2195 Al-Li alloy, a metallographic structure was observed at the bending area with severe plastic deformation.

Fig. 7 shows the metallographic structure of the 2195 Al-Li alloy under the CEF. It can be observed that the grains present elongated strip and the distribution of the grain shows obvious directionality under the single temperature field at 100 °C. The average length and width of the grains are 14.1 and 6.9 μm, respectively. It can also be seen that there are many second phase particles at the grain boundary with an average

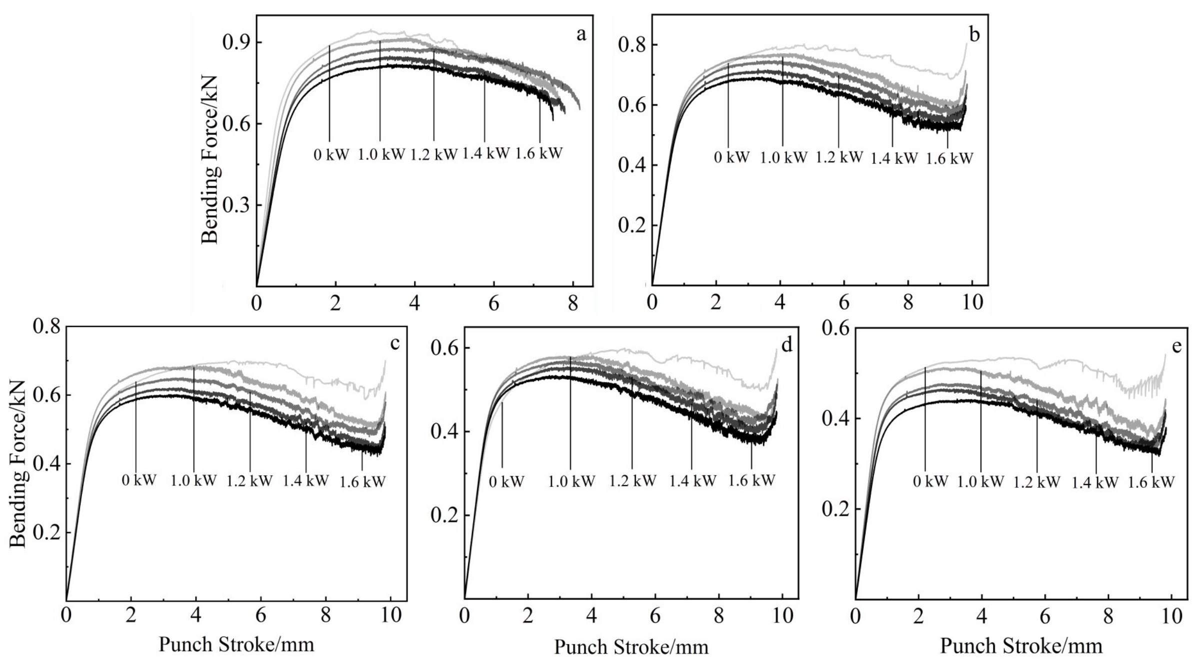

Fig.3 Bending force-punch stroke curves of 2195 Al-Li alloy sheets under the CEF at different temperatures: (a) 80 °C, (b) 100 °C, (c) 140 °C, (d) 170 °C, and (e) 200 °C

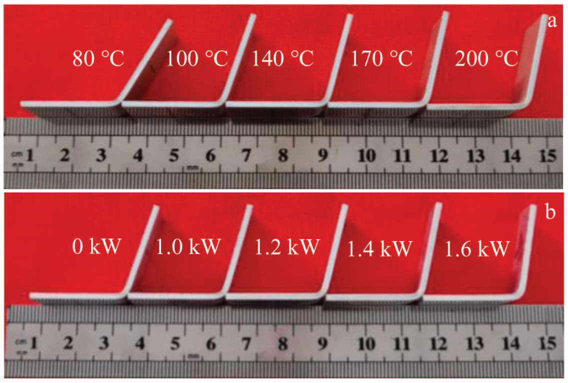

Fig.4 Bending specimens of 2195 Al-Li alloy under the CEF at different temperatures (a) and at 100 °C combined with different ultrasonic vibration energy (b)

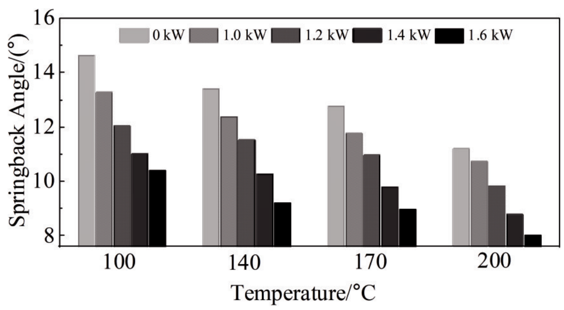

Fig.5 Springback angle of 2195 Al-Li alloy sheets under the CEF

size of 2.1 μm. And a few fine equiaxed subgrains appear in some areas. It shows that the material has a dynamic recovery phenomenon and a dynamic recrystallization tendency at this

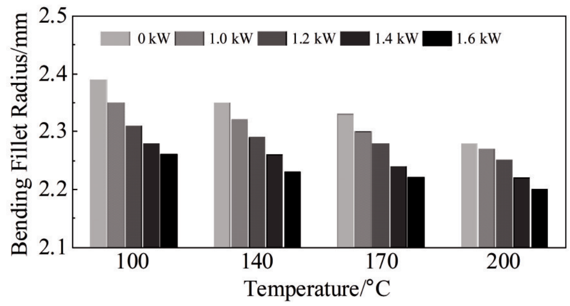

Fig.6 Bending fillet radius of 2195 Al-Li alloy sheets under the CEF

temperature.

When the temperature field is combined with the ultrasonic vibration energy-field (Fig. 7b and Fig. 7c), the second phase particle size increases because the ultrasonic vibration energy increases the activating energy of the material. The average size of the second phase particle is 3.8 and 4.2 μm under the CEF with 100 °C/1.2 kW and 100 °C/1.6 kW, respectively. Dynamic recrystallization is also enhanced, but compared with a single temperature field at 100 °C, the size of grain change is not apparent.

Furthermore, compared with the single temperature field at 100 °C, the metallographic structure of 2195 Al-Li alloy varies obviously under the single temperature field at 200 °C (Fig. 7d). Due to the increaseing temperature, significant dynamic recrystallization occurs and the average size of grain decreases. The average length and width of the grains is 9.7 and 4.4 μm, respectively. Simultaneously, the size of the dispersed second phase particles also increases significantly, with an average size of 6.7 μm.

The above analysis indicates that the high temperature

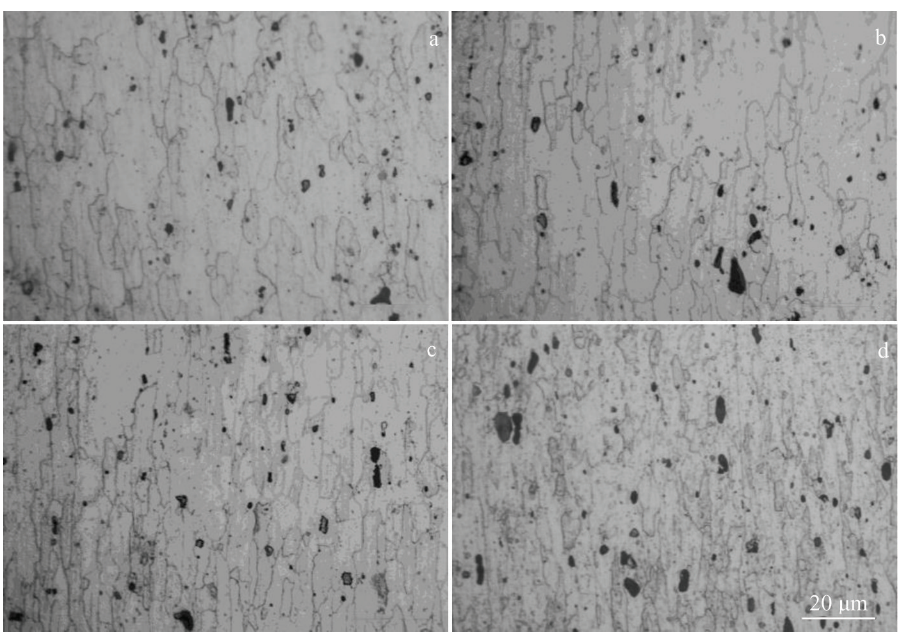

Fig.7 Metallographic structures of 2195 Al-Li alloy under the CEF: (a) 100 °C/0 kW, (b) 100 °C/1.2 kW, (c) 100 °C/1.6 kW, and (d) 200 °C/0 kW

softening effect of the material is further enhanced under the CEF. And the effect of inhibiting the springback and fracture of the bending part is equivalent to the effect of the single temperature field at a higher temperature. However, its influence on the metallographic structure is not as significant as the higher single temperature field.

3 Conclusions

1) The fracture and springback of 2195 Al-Li alloy during the 90° V-bending process can be inhibited under the CEF with 100~200 °C/1.0~1.6 kW.

2) Compared to a single temperature field, after the combination with the ultrasonic vibration energy-field, the high forming quality of 2195 Al-Li alloy can be achieved under a lower thermal condition, effectively reducing the temperature for hot forming of 2195 Al-Li alloy.

3) Due to the input of the ultrasonic vibration energy in the CEF forming process, the high temperature softening effect of the material is further enhanced. Moreover, the more the ultrasonic vibration energy input, the more pronounced the effect of improving the high temperature softening effect and bending quality of 2195 Al-Li alloy.

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温度/超声复合能场对2195铝锂合金弯曲性能的影响

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摘　要：针对铝锂合金弯曲成形过程中易产生破裂和回弹大的问题，进行了温度/超声复合能场下的弯曲工艺研究，希望在保证成形质量条件下借助超声振动能场降低铝锂合金弯曲成形温度。在80~200 ℃温度条件下通过与1.0~1.6 kW超声振动能量复合，分析了温度/超声复合能作用形式对2195铝锂合金板材弯曲力、弯曲回弹量、弯曲圆角半径及显微组织的影响。结果表明，通过与超声振动能场复合，在相对较低的热成形温度条件下，不仅降低了2195铝锂合金弯曲力，还有效抑制了2195铝锂合金弯曲回弹和破裂，从而提高了2195铝锂合金的高温软化效果和弯曲性能。

关键词：2195铝锂合金；温度/超声；复合能场；弯曲性能；微观组织

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