

Inhibiting bending springback of 2A97 Al-Li alloy using novel current-assisted in-situ heating technology

Guoxin Pang¹

gxpang@haust.edu.cn

Henan University of Science and Technology

Minghao Li

Dalian University of Technology

Guoqing Chen

Dalian University of Technology

XueWen Chen

Henan University of Science and Technology

Yanchao Jiang

Henan University of Science and Technology

Junqing Guo

Henan University of Science and Technology

Nan Xiang

Henan University of Science and Technology

Hairui Zhang

Henan University of Science and Technology

Research Article

Keywords: Current-assisted Springback correction In-situ heat treatment 2A97 Al-Li Alloy

Posted Date: October 15th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-11042286/v1>

License:   This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Additional Declarations: No competing interests reported.

Inhibiting bending springback of 2A97 Al-Li alloy using novel current-assisted in-situ heating technology

Guoxin Pang^{1*}, Minghao Li², Guoqing Chen², XueWen Chen¹, Yanchao Jiang¹, Junqing Guo¹, Nan Xiang¹, Hairui Zhang¹.

1. School of Materials Science and Engineering, Henan University of Science and Technology, Luoyang 471023, China

2. Key Laboratory of Solidification Control and Digital Preparation Technology (Liaoning Province), School of Materials Science and Engineering, Dalian University of Technology, Dalian 116085, PR China

*Corresponding author, gxpang@haust.edu.cn

Abstract: This study proposed a novel current-assisted in-situ heat treatment mold featuring a "metal matrix + rounded graphite" design for springback suppression in V-bending of 2A97 Al-Li alloy. The results demonstrated that the proposed mold structure can effectively suppress springback during the bending process. Comparative analysis of the forming accuracy, microstructure, and residual stress of the specimens before and after in-situ heat treatment reveals that the underlying mechanism lies in the combined effect of elevated temperature and electric current, which promotes stress relaxation and microstructural recovery. This facilitates the conversion of stored elastic strain energy into plastic deformation, thereby fundamentally reducing the driving force for elastic recovery. Consequently, springback is inhibited, and the forming accuracy of the workpiece is improved.

Key words: Current-assisted Springback correction In-situ heat treatment 2A97 Al-Li Alloy

1 Introduction

Driven by the growing demand for lightweighting in aerospace and transportation industries, aluminum-lithium (Al-Li) alloys have emerged as critical structural materials due to their excellent combination of high specific strength and high toughness^[1, 2]. As a typical representative of the third-generation Al-Li alloys, the 2A97 Al-Li alloy offers significant weight reduction while maintaining high strength and good damage tolerance, demonstrating broad application prospects^[3-5]. However, like other high-strength Al-Li alloys, 2A97 faces a major challenge during room-temperature plastic forming: springback^[6, 7]. This phenomenon is particularly pronounced in processes involving non-uniform deformation, such as bending and stretching, which severely limits the forming accuracy and dimensional stability of components, representing a key technical bottleneck for achieving precision forming.

Traditional methods for springback control and correction mainly rely on mold compensation^[8], optimization of process parameters^[9-11] (such as blank holder force and punch speed), and post-forming heat straightening^[12]. Nevertheless, these approaches have inherent limitations. Mold compensation heavily depends on empirical experience and iterative tryouts, leading to high development costs and long cycles. Process parameter optimization offers only a limited adjustable range and often yields unsatisfactory springback suppression for high-strength Al-Li alloys. Conventional heat straightening typically requires transferring the part to a dedicated heat treatment facility for prolonged overall heating, which not only consumes high energy and is inefficient but may also cause degradation of mechanical properties or induce new thermal distortions, failing to

meet modern manufacturing requirements for high precision, efficiency, and performance integration.

In recent years, current-assisted manufacturing technology ^[13-15] has gained considerable attention as an emerging thermo-mechanical coupled processing method. By applying a high-density electric current during plastic deformation, this technique leverages electroplastic effects ^[16, 17] (such as the Joule heating effect and electron wind force) to reduce the material's flow stress and enhance its deformability. Study^[18-20] have indicated that electric current can significantly influence the microstructure of metallic materials—promoting dislocation slip, multiplication, and annihilation, accelerating atomic diffusion, and even inducing dynamic recrystallization or recovery processes. This offers a novel strategy for performing rapid, localized, in-situ heat treatment on specific regions after deformation to eliminate residual stress and suppress springback. Compared with traditional global heating methods, the current-assisted approach offers notable advantages, including localized energy input, rapid response, precise temperature control, and lower energy consumption, demonstrating great potential for efficient and accurate springback correction.

Hence, the present study focuses on the 2A97 Al-Li alloy and aims to develop a current-assisted in-situ correction method for its V-bending springback. The research comprises two main aspects: investigating the influence of mold structure on springback, and analyzing the microstructural evolution of the material under electric current, combined with changes in residual stress, to elucidate the underlying mechanism of springback suppression. This work intends to provide an efficient and controllable process solution for the precision bending of high-strength Al-Li alloys.

2 Experimental materials and methods

2.1 Experimental materials

The material used in this study was a 2.2 mm thick hot-rolled sheet of 2A97 Al-Li alloy supplied by the Light Alloy Research Institute Co., Ltd. To eliminate the influence of rolling residual stress, all V-bending specimens underwent solution treatment prior to bending experiments. Based on references ^[21, 22], the solution treatment was conducted at 510 °C for 1 hour, followed by water quenching. The microstructure after solution treatment was characterized using electron backscatter diffraction (EBSD). The results are shown in Fig. 1: The inverse pole figure (IPF) map in Fig. 1a reveals that the sample primarily consists of coarse lamellar grains elongated along the rolling direction (RD), with an average thickness of about 24 μm and an average length of approximately 195 μm . The kernel average misorientation (KAM) map in Fig. 1b indicate that the interior of the grains is dominated by low KAM values (blue regions), with an average KAM of only $\bar{\theta} = 0.18^\circ$. This suggests a low local orientation gradient and a reduced density of geometrically necessary dislocations within the material, confirming the adequacy of the solution treatment.

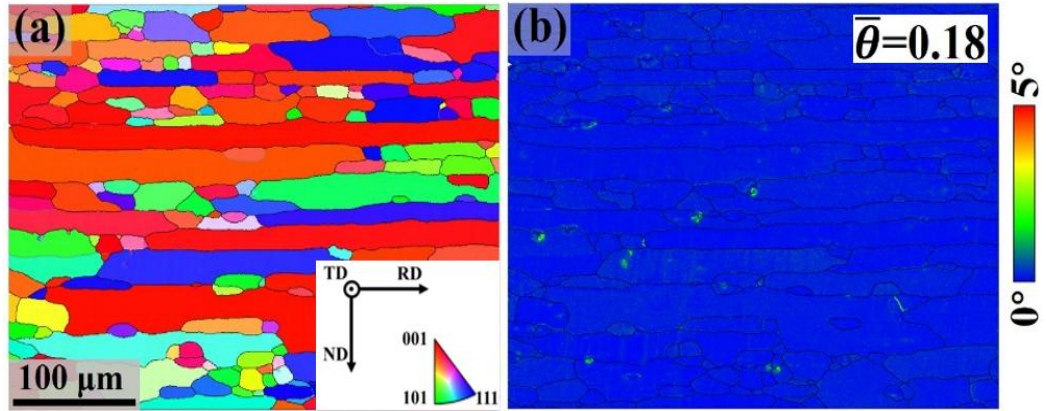


Fig. 1 Microstructure of as-quenched 2A97 Al-Li alloy: (a) IPF map; (b) KAM map.

The current-assisted in-situ heat correction was conducted subsequent to the current-assisted V-bending process. The morphology of the sample after V-bending is presented in Fig. 2. The presence of springback is evidenced by the discrepancy between the theoretical bend angle and radius ($\alpha = 31^\circ$, $r = 2$ mm) and the actual measured values ($\alpha = 32.5^\circ$, $r = 2.2$ mm). The corresponding microstructural characteristics of the bent sample are shown in Fig. 3.

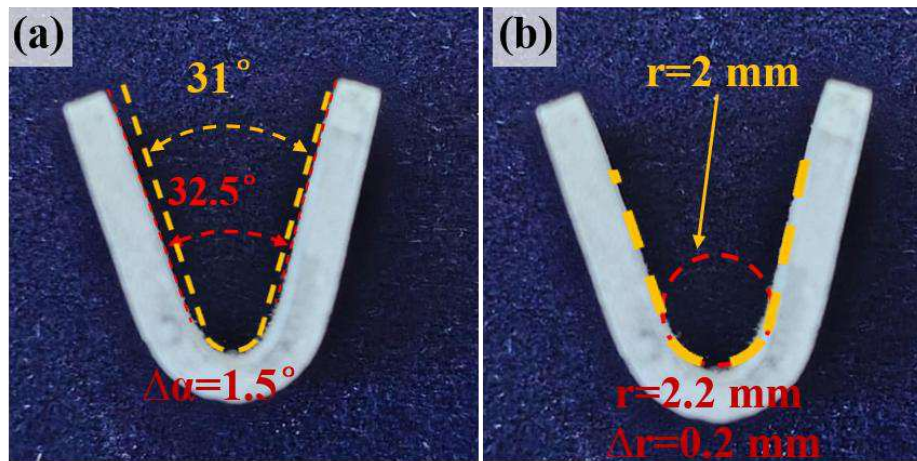


Fig. 2 Comparison diagram of sample bending angle and bending radius before and after V-bending.

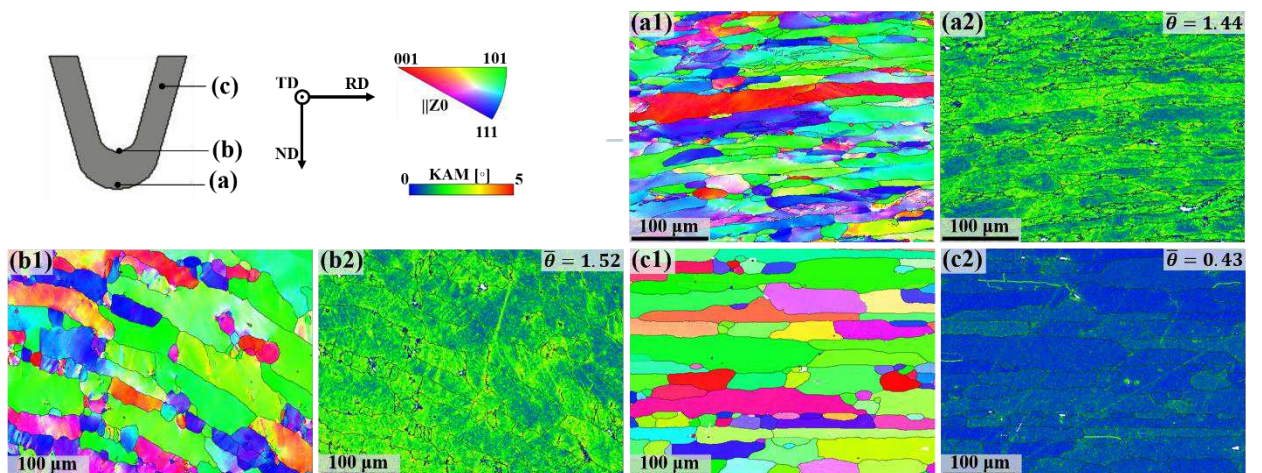


Fig. 3 After V-bending, the microstructure of samples at different positions: (a) outside the bending angle; (b) inside of bending angle; (c) non-deformed area of side wall.

2.2 Mold structure of current-assisted in-situ heat treatment

Physical photographs and schematic diagrams of the two current-assisted in-situ heat treatment molds used in this study are presented in Fig. 4. For clarity, the configurations shown in Fig. 4 (a1, b1) are designated as mold #1 and mold #2, respectively. Both molds feature a punch (connected to the positive electrode) with a composite "metal matrix + rounded graphite" design. This design leverages the high resistivity of graphite to achieve localized concentrated heating when the current passes through, thereby effectively minimizing heat dissipation via the punch.

The current path, illustrated in Fig. 4 (b1, b2), flows sequentially through the graphite punch corner, the bend corner of the specimen, and finally to the lower mold (negative electrode), completing the circuit. To investigate the influence of thermal conductivity on process efficiency, two different materials were used for the lower mold, which constitutes the key difference between mold #1 and mold #2: mold #1 employs a graphite lower mold, whereas mold #2 uses a 316L stainless steel lower mold. A spring-loaded mechanism ensured tight contact between the lower mold and the specimen to prevent arcing.

The heat treatment parameters were set as follows: the specimen was heated until the maximum temperature in the target zone reached 500 °C, held for 30 seconds, and then subjected to power-off and unloading. The temperature was monitored in situ throughout the process using an infrared thermal camera.

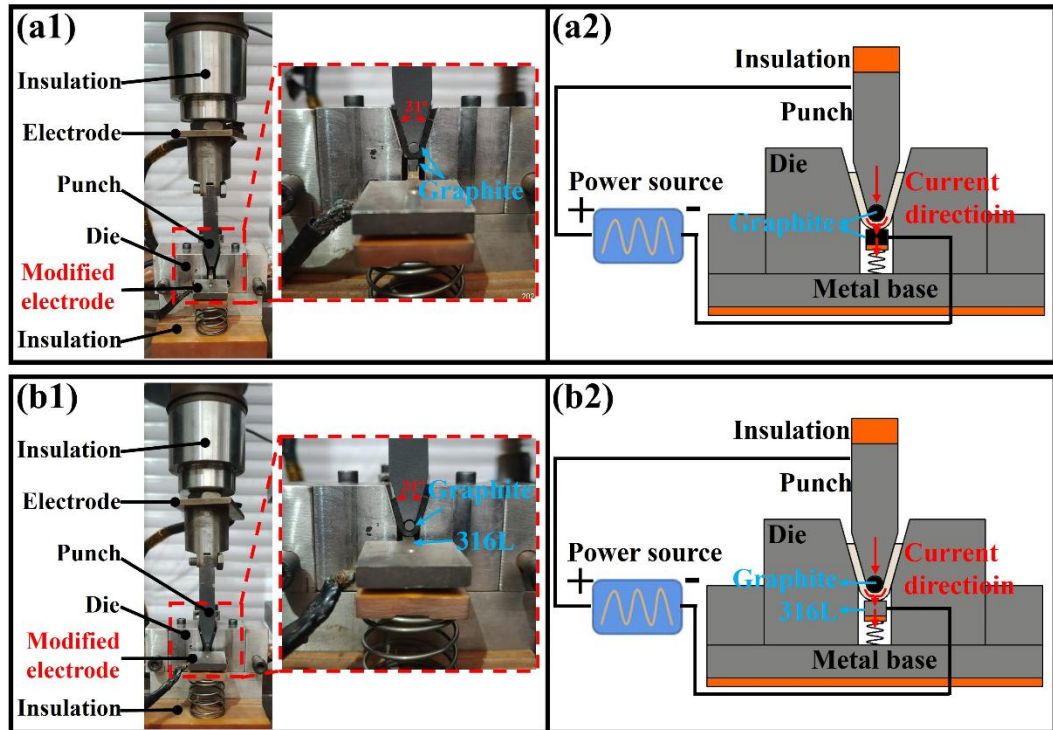


Fig. 4 Physical and schematic drawings of current-assisted in-situ heat treatment molds of different constructions: (a1)-(b1) physical drawings; (a2)-(b2) schematic drawings.

2.3 Pulse current parameter setting and residual stress characterization

The pulse power supply is a GGDF-1000 A/12 V DC pulse power supply produced by Guangzhou Huaxing Power Technology Co., Ltd., with a maximum pulse current of 1000 A. The

pulse frequency can be adjusted between 0-100 Hz, and the duty cycle can be adjusted between 10-100%. The current signal output by the pulse power supply was recorded and monitored by a Tektronix TDS-1000B oscilloscope. The parameters during in-situ heat treatment are: peak current of 220 A, pulse frequency of 100 Hz, and duty cycle of 20%. Fig. 5 shows the waveform of the pulse current.

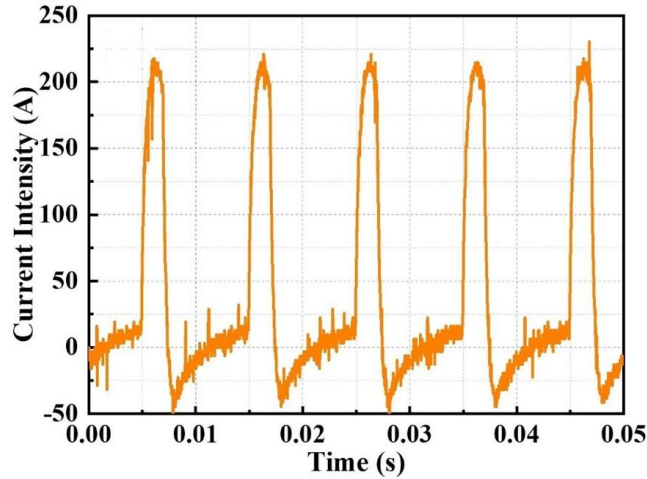


Fig. 5 The pulse current waveform

The residual stress in the specimens after bending and in-situ heat treatment was determined using an XL-60 stress diffractometer (manufactured by Aisite Stress Technology Co., Ltd., Handan, China). Measurements were taken at the outer corner of the bend angle, corresponding to location (a) in Fig. 3. The testing parameters were as follows: Cu target, a collimator diameter of 0.5 mm, an accelerating voltage of 26 kV, and a current of 6 mA.

3 Results and Discussion

3.1 Temperature distribution during in-situ heat treatment

Fig. 6 presents the temperature distributions of the bent 2A97 Al-Li alloy specimens during current-assisted in-situ heat treatment using the two different mold configurations. It is noteworthy that in both cases, the region exceeding 500 °C was not located within the specimen itself but was concentrated on the graphite lower mold (mold #1) and the graphite punch corner (mold #2), respectively. Comparative analysis, however, reveals that mold #1, featuring a fully graphite current path (including the graphite lower mold), offers distinct advantages: the bend region of the specimen reached a higher temperature (470°C), exhibited a more uniform temperature distribution both through-thickness and along the length, and required a lower applied current density (16 A/mm²) to achieve this thermal state. These results clearly indicate that for materials like the 2A97 Al-Li alloy, which possess high thermal conductivity and low electrical resistivity, the mold design in contact-based electro-assisted heat treatment must be optimized to mitigate heat dissipation through the electrodes. Given the decisive influence of the temperature field on the final forming outcome, the subsequent analysis will focus on comparing the springback correction results and microstructural evolution in specimens treated with mold #1 and mold #2.

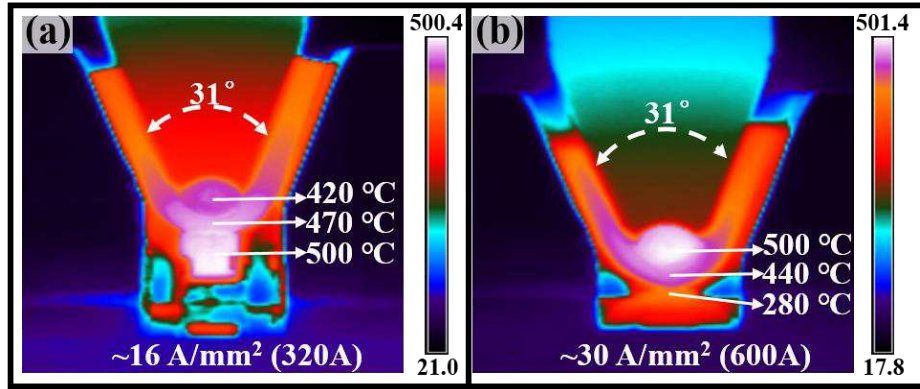


Fig. 6 Temperature distribution of 2A97 Al-Li alloy when heat-treated in-situ by different molds: (a) mold 1#; (b) mold 2#.

3.2 Sample accuracy after heat treatment

Fig. 7 shows the macroscopic morphologies of the bent 2A97 Al-Li alloy specimens after current-assisted heat treatment using the two molds. Comparison with the pre-treatment state (Fig. 2) confirms that both schemes effectively eliminated springback: the final bend angle was corrected to 31° with an inner radius consistently within the 1.95–2 mm range, showing excellent agreement with the theoretical mold dimensions. This indicates that, in terms of the final forming accuracy, both mold designs can be successfully applied for springback correction of the 2A97 Al-Li alloy bend components. However, when considering process efficiency and temperature field quality comprehensively, mold #1 demonstrates clear superiority, as it required a lower current density and produced a more uniform temperature distribution within the specimen. Therefore, mold #1 is considered the preferred and optimized solution.

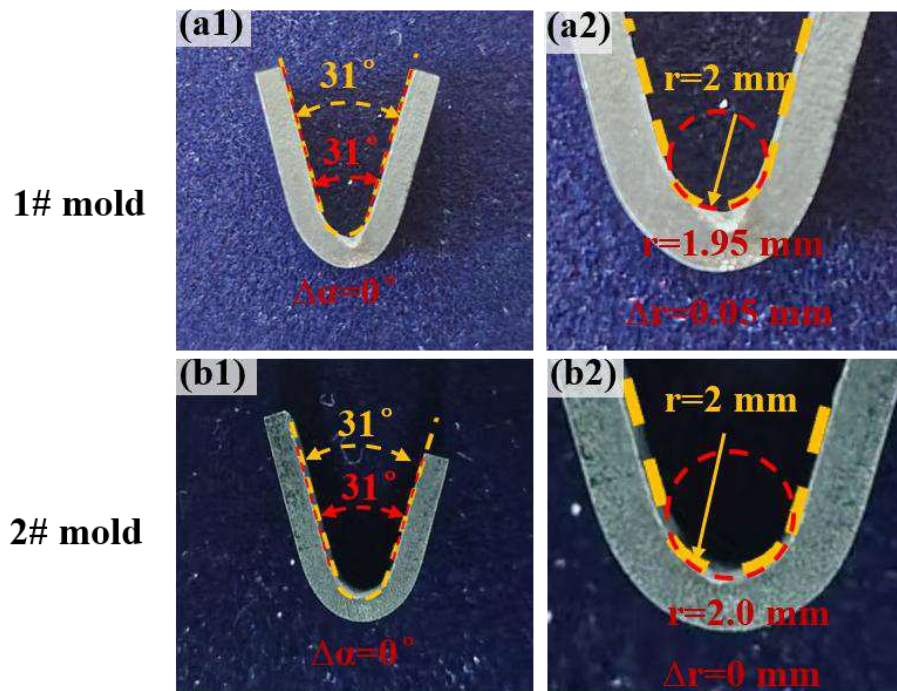


Fig. 7 Specimens of 2A97 Al-Li alloy after bending by different molds: (a1)-(a2) mold #1; (b1)-(b2) mold #2 .

3.3 Microstructure after bending

Fig. 8 presents the EBSD analysis results from different regions of the bent specimen after heat treatment with mold #1. The IPF maps in Fig. 8 (a1)-(b1) show that, within the bend corner region, fine equiaxed grains are present alongside the original coarse lamellar grains, suggesting the occurrence of localized static recrystallization during the heat treatment. More importantly, the KAM maps in Fig. 8 (a2)-(b2) reveal a significant reduction in local misorientation inside the coarse grains. The average KAM values at the inner and outer bend corners decreased to 0.52 and 0.56, respectively, which are substantially lower than the pre-treatment values of 1.52 and 1.44. This remarkable decrease in KAM values provides direct evidence of static recovery processes, leading to a considerable reduction in dislocation density and the effective release of internal stresses. This observation offers a microstructural explanation for the effective suppression of springback.

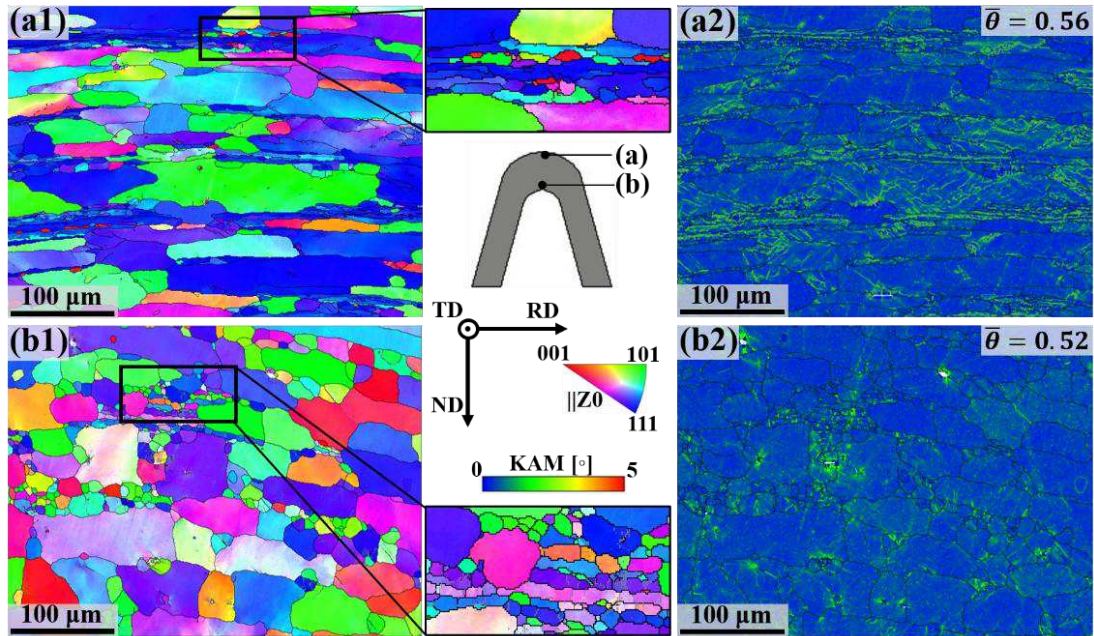


Fig. 8 EBSD results of 2A97 Al-Li alloy bending specimens at different positions after in-situ heat treatment by mold #1: (a1)-(b1) IPF maps; (a2)-(b2) KAM mapping.

3.4 Mechanism of reducing springback by electric assisted in-situ heat treatment

The springback mechanism in sheet metal bending, which involves both elastic-plastic deformation, can be attributed to two primary factors upon unloading: the recovery of elastic deformation and the redistribution/release of internal residual stresses (in Fig. 9). Based on the experimental results presented above, where springback was effectively eliminated after current-assisted in-situ heat treatment, it can be reasonably inferred that the two fundamental drivers of springback—elastic strain energy and residual stress—were significantly reduced under the coupled thermal-electrical field, thereby effectively suppressing springback.

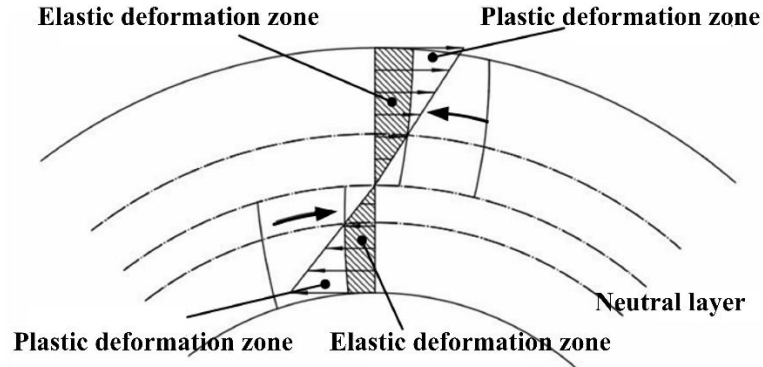


Fig. 9 Schematic diagram of sheet bending deformation

After unloading, the elastic recovery can be considered as applying a reverse bending moment M to the part. The resulting springback angle $\Delta\theta$ can be calculated by the following formula ^[23, 24]:

$$\Delta\theta = 2 \int_0^{\theta} \frac{M}{EI} R_n d\alpha$$

Where, $M = 5(r_p + 0.4\sigma_b)(A_1 - A_2 \int_0^{0.4} f(y)dy)$, $\Delta\theta$ represents springback angle caused by elastic recovery; E represents Young's modulus; I moment of inertia of unit width cross section; R_n represents radius of neutral layer; r_p represents punch radius; σ_b represents yield strength; $f(y)$ represents functions related to elastic deformation; y represents distance to neutral layer; A_1 , A_2 represents constant coefficient.

According to this theoretical model, with fixed part geometry, the springback angle primarily depends on the material's yield strength and Young's modulus. A decrease in yield strength or an increase in Young's modulus reduces springback. Elevated temperature significantly lowers the yield strength, thereby reducing the bending moment and inhibiting elastic recovery. Furthermore, the stress relaxation effect during high-temperature holding under constraint is crucial: under a constant total strain, thermal activation promotes dislocation slip and climb, leading to stress decay over time, which also reduces the bending moment. Research indicates that introducing an electric current can intensify this process. For instance, Zhan et al. ^[25] found that electric current reduces the apparent activation energy for stress relaxation in 2219 Al-Li alloy, accelerating the relaxation rate. Similarly, Zhao et al. ^[26] reported that current enhances stress relaxation and promotes phase transformation in TC4 titanium alloy, collectively leading to stress softening. Thus, within the coupled thermal-electrical field, the electric current significantly accelerates stress relaxation, promoting a reduction in the internal stress level of the specimen and thereby more effectively diminishing elastic recovery.

To validate the above mechanism, the change in the elastic bending moment can be assessed by comparing the residual stress on the outer bend surface before and after heat treatment. The underlying principle is illustrated in Fig. 10: during bending, the outer surface is in tension and the inner surface in compression. After unloading and springback, due to elastic recovery, the outer surface exhibits residual compressive stress while the inner surface shows residual tensile stress. A higher elastic bending moment corresponds to a greater magnitude of these residual stresses. Therefore, measuring the change in residual stress on the outer bend surface directly demonstrates the effect of the in-situ heat treatment in reducing the elastic bending moment.

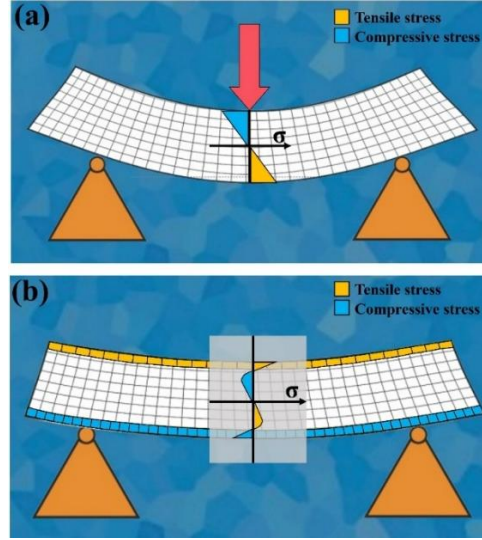


Fig. 10 Stress distribution in bending forming: (a) stress distribution in bending specimen; (b) stress distribution in bending specimen after unloading.

The residual stress measurements obtained before and after heat treatment using the XL-640 stress diffractometer are presented in Fig. 11. The data indicate that a residual compressive stress of 68.1 MPa was present on the outer surface of the bend corner after springback. Following the in-situ heat treatment, this compressive stress was not only eliminated but was also converted into a tensile stress of 13.9 MPa, representing a substantial reduction in its absolute magnitude. This measurement is consistent with the notable decrease in the KAM values observed in the aforementioned EBSD analysis (comparing Fig. 3 with Fig. 8), collectively confirming that the internal residual stress within the specimen was effectively relieved by the current-assisted in-site heat treatment.

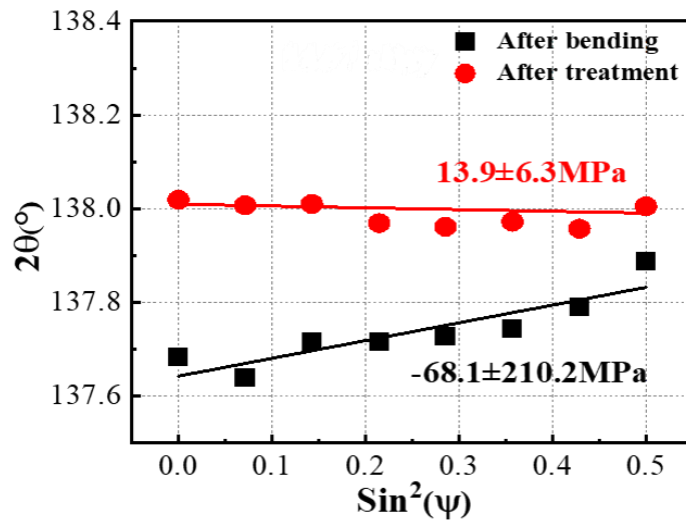


Fig. 11 Residual stresses on the outer surface of the bent corner before and after in-situ heat treatment. Note: 2θ represents the diffraction angle and $\sin^2(\Psi)$ represents the inclination degree.

The above results demonstrate that the current-assisted in-situ heat treatment, through the synergistic thermal-electrical effect, successfully eliminated the elastic recovery strain in the bent specimen and significantly mitigated the residual stress induced by plastic deformation.

Consequently, springback was markedly suppressed, leading to a substantial improvement in the forming accuracy of the component.

4 Conclusions

This study developed a current-assisted in-situ heat treatment die based on a composite " metal matrix + rounded graphite " electrode, successfully demonstrating its efficacy in suppressing V-bending springback of 2A97 Al-Li alloy. The underlying mechanism is attributed to the promoted stress relaxation and microstructural recovery within the material under the coupled thermal-electrical field, which facilitates the conversion of elastic strain energy into plastic dissipation, thereby fundamentally mitigating the driving force for springback. The findings provide a viable and effective strategy for achieving precise bending of high-strength Al-Li alloys.

Acknowledgements

This work was financial supported by the National Natural Science Foundation of China [grant numbers: 52075073, U1908229].

Data and code availability

All data and code generated or analysed during this study are included in this published article.

Declaration of Interests Statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References:

- [1] Y. LÜ, X. MENG, Y. LI, Z. DONG, X. ZHANG, Corrosion behavior of 2A97 Al–Cu–Li alloys in different thermomechanical conditions by quasi-in-situ analysis, *Transactions of Nonferrous Metals Society of China*, 34(2024) 2772-2786.
- [2] K. Chen, X. Wu, Y. Cao, Z. Wang, X. Zhang, C. Wu, M. Chen, Enhanced strength and ductility in an Al–Cu–Li alloy via long-term ageing, *Materials Science and Engineering a-Structural Materials Properties Microstructure and Processing*, 811(2021) 141092.
- [3] M. Li, Y. Zu, G. Chen, Y. Li, X. Li, Ultrafast recrystallization and grain refinement of 2A97 Al-Cu-Li alloy by electropulsing assisted annealing at lower temperature, *Journal of Alloys and Compounds*, 1003(2024) 175662.
- [4] C. Gao, R. Gao, Y. Ma, Microstructure and mechanical properties of friction spot welding aluminium–lithium 2A97 alloy, *Materials & Design*, 83(2015) 719-727.
- [5] Y. Liu, C. Zhao, J. Chen, R. Liu, J. Jiang, X. Cui, S. Liang, H. Chi, L. Zou, Effects of pre-strain deep cryogenic aging on the mechanical and corrosion properties of 2A97 aluminum–lithium alloy, *Journal of Materials Research and Technology-JMR&T*, 30(2024) 2728-2737.
- [6] Y. Zhi, Y. Feng, D. Wang, X. Hu, T. Sun, X. Liu, Forming Characteristics of Tailor Rolled Blank of Aluminum Alloy during Three-Point Bending, *Materials*, 17(2024) 591.
- [7] R.W. Said, M. Mehrabi, Parametric study of part dimensional variations due to spring-back effects in deep drawing: theory and experiment, *International Journal of Advanced Manufacturing Technology*, 127(2023) 5171-5183.
- [8] W. Xiong, Z. Gan, S. Xiong, Y. Xia, Rapid Springback Compensation for Age Forming Based on Quasi Newton Method, *Chinese Journal of Mechanical Engineering*, 27(2014) 551-557.
- [9] T.S. Alhalaybeh, Y. Muhamaiti, H. Shang, L. Zhou, X. Liang, Y. Lou, Artificial neural network based stamping process design for three-point bending, 42(2026) 424895.
- [10] M.A.H. Mithu, M.A. Karim, F.A. Taj, A. Rahman, Predicting springback in V-bending: Effects of load, load holding time, and heat treatment on common sheet-metal forming operations, *Materials Today Communications*, 43(2025) 111668.
- [11] Y. Feng, S. Shi, Z. Wang, Z. Wang, Research on mechanism of springback control by viscous medium with different mechanical properties, *Journal of Materials Processing Technology*, 304(2022) 117548.
- [12] H. Xie, Q. Wang, K. Liu, F. Peng, X. Dong, J. Wang, Investigation of influence of direct-current pulses on springback during V-bending of AZ31B magnesium alloy sheet, *Journal of Materials Processing*

- Technology, 219(2015) 321-327.
- [13] D. Dobras, Z. Zimniak, M. Zwierzchowski, M. Dziubek, Microstructure and mechanical properties of AlMg3 alloy in different hardening states during pulsed current assisted tensile deformation, *Journal of Alloys and Compounds*, 1036(2025) 181640.
 - [14] Z. Niu, Z. Yue, Z. Xia, W. Liu, S. Zhang, A. Xu, A generalized electro-thermo-mechanical framework for electrically assisted tube forming: Case study on TA18 titanium alloy, *Journal of Materials Processing Technology*, (2025).
 - [15] C. Chen, G. Xiao, Q. Xia, J. Zhang, S. Cheng, Macroscopic and microscopic deformation mechanism of cup-shaped part made of difficult-to-deform metal during the current-assisted flow spinning process, *Journal of Materials Processing Technology*, 340(2025) 118859.
 - [16] A.F. Sprecher, S.L. Mannan, H. Conrad, Overview no. 49: On the mechanisms for the electroplastic effect in metals, *Acta Metallurgica*, (1986).
 - [17] S. Xiang, X. Zhang, Dislocation structure evolution under electroplastic effect, *Materials Science and Engineering a-Structural Materials Properties Microstructure and Processing*, 761(2019) 138026.
 - [18] R. Delville, B. Malard, J. Pilch, P. Sittner, D. Schryvers, Microstructure changes during non-conventional heat treatment of thin Ni–Ti wires by pulsed electric current studied by transmission electron microscopy, *Acta Materialia*, 58(2010) 4503-4515.
 - [19] W. Zeng, Y. Shen, N. Zhang, X. Huang, J. Wang, G. Tang, A. Shan, Rapid hardening induced by electric pulse annealing in nanostructured pure aluminum, *Scripta Materialia*, 66(2012) 147-150.
 - [20] M. Kim, K. Lee, K.H. Oh, I. Choi, H. Yu, S. Hong, H.N. Han, Electric current-induced annealing during uniaxial tension of aluminum alloy, *Scripta Materialia*, 75(2014) 58-61.
 - [21] Q. Liu, G. Fan, Z. Tan, Z. Li, D. Zhang, J. Wang, H. Zhang, Precipitation of Al₃Zr by two-step homogenization and its effect on the recrystallization and mechanical property in 2195 Al–Cu–Li alloys, *Materials Science and Engineering a-Structural Materials Properties Microstructure and Processing*, 821(2021) 141637.
 - [22] C. Zhou, L. Zhan, H. Li, Improving creep age formability of an Al–Cu–Li alloy by electropulsing, *Journal of Alloys and Compounds*, 870(2021) 159482.
 - [23] D. Zhang, Z. Cui, X. Ruan, Y. Li, An analytical model for predicting springback and side wall curl of sheet after U-bending, *Computational Materials Science*, 38(2007) 707-715.
 - [24] D. Ao, X. Chu, Y. Yang, S. Lin, J. Gao, Effect of electropulsing on springback during V-bending of Ti-6Al-4V titanium alloy sheet, *International Journal of Advanced Manufacturing Technology*, 96(2018) 3197-3207.
 - [25] L. Zhan, Z. Ma, J. Zhang, J. Tan, Z. Yang, H. Li, Stress relaxation ageing behaviour and constitutive modelling of a 2219 aluminium alloy under the effect of an electric pulse, *Journal of Alloys and Compounds*, 679(2016) 316-323.
 - [26] Y. Zhao, L. Peng, X. Lai, Influence of the electric pulse on springback during stretch U-bending of Ti6Al4V titanium alloy sheets, *Journal of Materials Processing Technology*, 261(2018) 12-23.