

# Predicting Springback via a Stress-based Indicator

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We present a stress-based indicator for predicting and evaluating the springback behavior of 7075 high-strength aluminum alloy during warm (150 and 250 °C) and hot (490 °C) forming through experiments and numerical simulations. The results indicate that while hot forming yields the minimum springback, the springback angles in warm forming are notably higher and exhibit a decreasing trend as the forming temperature increases. To clarify this behavior, the total absolute stress differential ( $S_{total}$ ) is introduced to quantify the through-thickness stress imbalance. By integrating the numerical model with press equipment parameters including blank holder forces and positions, the  $S_{total}$  indicator can be used as a computational sensor for monitoring internal stress states. The findings suggest that the reduction in springback at higher temperatures is driven by a marked decrease in the accumulated stress differential, demonstrating a clear positive correlation between these two physical quantities. This work provides a robust mechanical basis for the potential real-time adjustment of forming conditions, facilitating the intelligent quality control of high-strength aluminum alloys at elevated temperatures.

## 1. Introduction

To comply with increasingly stringent CO<sub>2</sub> emission standards, automotive manufacturers have a continuous need for vehicle lightweighting. Aluminum alloy sheets, with a density of only one-third that of steel, offer superior lightweighting advantages. As a result, they are being increasingly adopted for body structures and closure panels to replace traditional steel components. To overcome the challenges of the limited formability of high-strength aluminum alloys at room temperature, international research to investigate warm and hot forming technologies,<sup>(1,2)</sup> which exploit the enhanced formability of aluminum alloys at elevated temperatures, has been started. Warm forming typically involves heating aluminum alloy sheets in T4 or T6 tempers to a specific temperature range (150–250 °C) before forming, which mitigates the springback of the formed components and leads to better dimensional stability.<sup>(3,4)</sup> In contrast, the hot forming technology pioneered by Lin and others in the early 2000s involves forming at even higher temperatures (>450 °C) where the material exhibits significantly

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enhanced ductility.<sup>(5–15)</sup> In this process, aluminum sheets in the F temper are heated to the solution heat treatment temperature, followed by forming and die quenching. Die quenching refers to the rapid cooling of the high-temperature blank during the die-closing stage, where the heat is quickly dissipated through contact with the cooler die surfaces to achieve a quenching effect. Subsequently, artificial ageing is conducted to restore the mechanical strength of the formed parts. To the best of the authors' knowledge, the relationship between springback and internal stress imbalance in warm and hot forming processes has not yet been comprehensively investigated. In this study, the springback characteristics of 7075 high-strength aluminum alloy in both warm and hot forming processes were analyzed through a combination of numerical simulations and experimental validation. The developed stress-based indicator ( $S_{total}$ ) has the potential to serve as a computational sensor for monitoring internal stress states by integrating numerical analysis with real-time press parameters, such as blank holder forces and positions. This approach provides a robust mechanical basis for the future dynamic adjustment of forming conditions, facilitating the intelligent quality control of high-strength aluminum alloy components.

## 2. Materials and Methods

In this study, 2-mm-thick 7075-T6 aluminum alloy sheets with a hardness of 184 HV were utilized for warm forming, whereas 7075-F sheets with an initial hardness of 113.2 HV were used for hot forming. A hat-shaped die was employed for experimental testing, and numerical simulations were performed using PAM-STAMP finite element simulation software to evaluate the springback behavior under warm (150 and 250 °C) and hot (490 °C) forming conditions. For experimental validation, the springback of the formed parts was quantified via ATOS 3D scanning. We specifically examine the correlation between through-thickness stress distribution, particularly the stress differential between the upper and lower surfaces, and the final springback behavior.

### 2.1 Numerical model

A finite element model was developed using PAM-STAMP software, as illustrated in Fig. 1. The simulation sequence encompasses several stages: blank positioning, holding, forming with die quenching, and springback. The blank holding force was set at 20 kN, with a die quenching time of 10 s under a die clamping force of 800 kN.

For the warm forming process, the sheet temperatures were set at 150 and 250 °C, while the hot forming process was conducted at 490 °C. The coefficient of friction between the sheet and the tool was set to 0.25. The flow stress curves at elevated temperatures, which serve as the material input for the numerical model, are presented in Fig. 2. During the forming process, the blank holder first secures the sheet. Subsequently, the upper die moves downward to perform the bending operation. Once the upper die reaches the bottom dead center, the sheet is formed into a hat-shaped profile. Upon tool release, the part undergoes springback due to the release of internal stresses under unconstrained conditions.

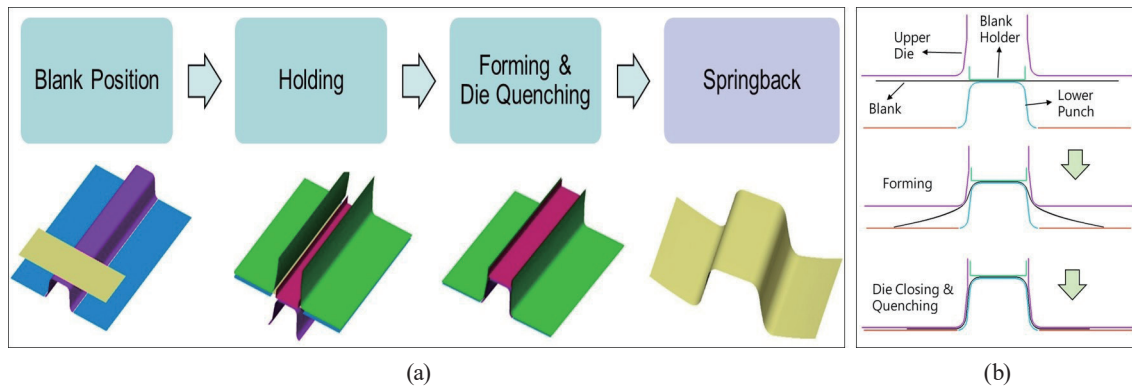


Fig. 1. (Color online) (a) Simulation procedure for the springback of warm and hot forming and (b) cross-sectional view of the forming process.

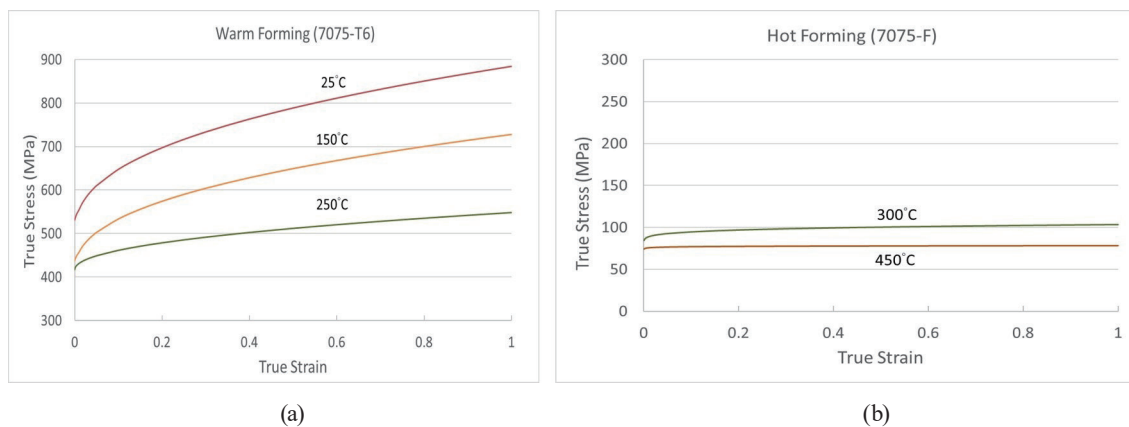


Fig. 2. (Color online) Flow stress curves at elevated temperature used in the simulation for (a) warm forming and (b) hot forming.

Figure 3 shows the measurement method and definition of the springback angle within the numerical model. To evaluate the dimensional change, a cross section was extracted at the midplane of the part to measure the springback angle ( $\theta$ ) between the sidewall and the top surface.

## 2.2 Experiments

Hat-shaped parts were formed under various conditions for both warm and hot forming, as shown in Fig. 4. The aluminum alloy sheets were prepared with dimensions of 200 mm  $\times$  80 mm. To ensure reproducibility, each forming condition was repeated using three separate specimens.

The heating process was conducted in a furnace with a temperature stability of  $\pm 5$  °C, ensuring a consistent thermal history for all specimens. For warm forming, the 7075-T6 sheets were preheated in a furnace for 15 min to reach the target temperatures (150 and 250 °C). The heated sheets were then transferred to the die with a controlled transfer time of approximately

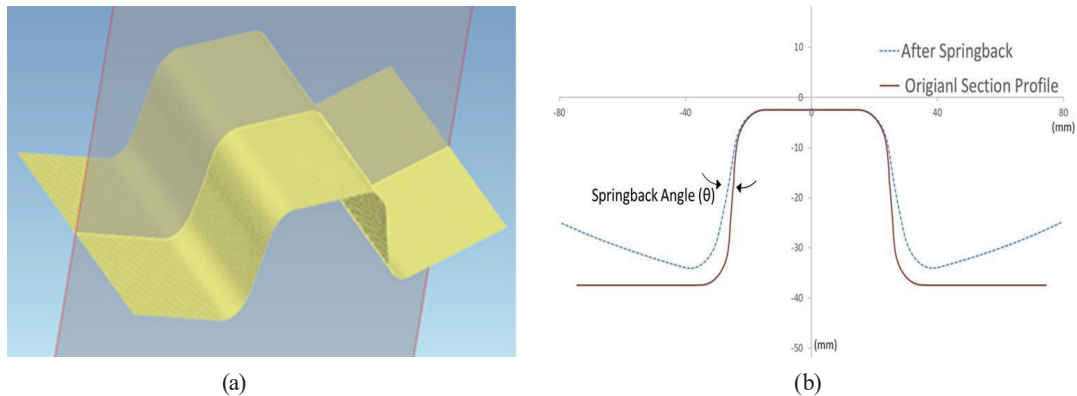


Fig. 3. (Color online) (a) Schematic of the sectioning plane for springback measurement and (b) definition of springback angle ( $\theta$ ).

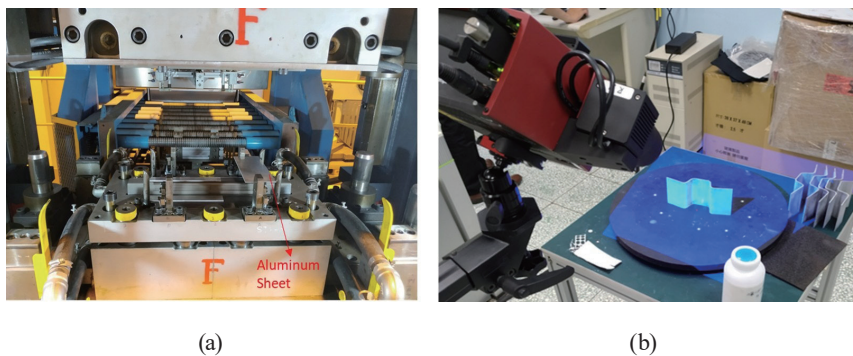


Fig. 4. (Color online) (a) Experimental setup for the warm/hot forming of hat-shaped parts and (b) ATOS 3D scanner for profile measurement.

3–5 s. The transfer time was maintained as consistent as possible to ensure uniform temperature drop during the blank transfer process, thereby minimizing the impact of temperature fluctuations on the forming conditions and springback behavior. Subsequently, the sheets were formed with a blank holder force of 20 kN and a clamping force of 800 kN during die quenching. The die quenching duration was set at 10 s. For hot forming, 7075-F sheets were used and heated to the solution heat treatment temperature of 490 °C for 20 min. Following the transfer to the die, the parts were formed and quenched using the same parameters as in the warm forming process. The hot-formed parts were subsequently placed in an oven for artificial ageing at 120 °C for 24 h. As illustrated in Fig. 5, the springback angles at the center cross sections of the components were measured using an ATOS noncontact scanner with a spatial resolution accuracy of  $\pm 0.01$  mm.

### 3. Results and Discussion

The measured springback angles for the warm and hot forming processes are presented in Fig. 5, where each reported value represents the average of three specimens. The experimental results indicate that warm forming exhibits a notably larger springback than hot forming. Within

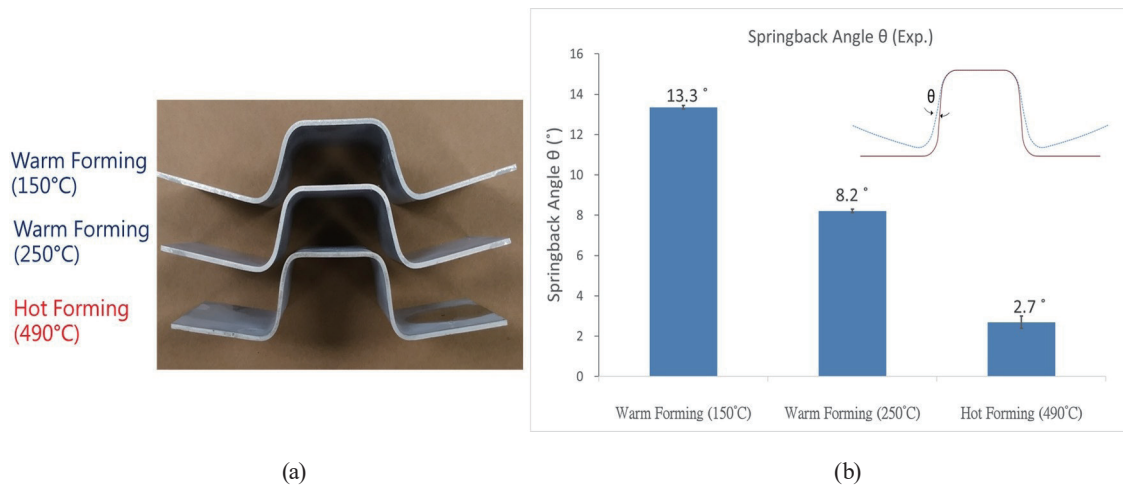


Fig. 5. (Color online) (a) Profiles of parts formed under warm and hot forming conditions and (b) measured springback angles ( $N = 3$ ).

the warm forming regime, the springback magnitude decreases as the forming temperature increases. Specifically, the average springback angles ( $N = 3$ ) for warm forming at 150 and 250 °C, and hot forming at 490 °C were 13.3, 8.2, and 2.7°, respectively. Please note that the error bars appear relatively small because the experimental results demonstrated excellent repeatability, with standard deviations of 0.087, 0.088, and 0.303° for the respective conditions. This high level of consistency proves the stability of the forming process and measurement. Generally, sheet metals formed under higher flow stress retain greater residual stresses, and the subsequent stress relaxation upon tool release leads to more pronounced springback. As shown in Fig. 2, the flow stress of 7075-T6 during hot forming at 490 °C is below 100 MPa, which accounts for the minimal springback observed. The significant reduction of springback in hot forming (490 °C) can also be explained by the dynamic recrystallization and recovery occurring near the solution treatment temperature. These microstructural evolutions markedly lower the yield strength and eliminate the internal stress.<sup>(16)</sup>

The numerical model was utilized to investigate the stress differential between the upper and lower surfaces, which is calculated as the upper surface major stress minus the lower surface major stress, along the central cross section of the hat-shaped part, as shown in Fig. 6. Overall, in the fully formed state before tool release, the stress differential for warm forming at 150 °C is greater than that at 250 °C, while hot forming at 490 °C exhibits the minimum value. As highlighted in the black-boxed areas, the stress differentials in critical regions, including the die radius ( $R_d$ ), sidewall, and punch radius ( $R_p$ ), significantly affect the final springback behavior. In these specific regions, the stress differential is highest at 150 °C, followed by that at 250 °C, and the lowest at 490 °C. These simulation findings are highly consistent with the experimental springback data presented in Fig. 5, where the springback angle is largest at 150 °C, followed by that at 250 °C, and smallest at the hot forming temperature of 490 °C. This indicates that a higher stress differential prior to tool release directly correlates with more pronounced springback in the final formed parts.

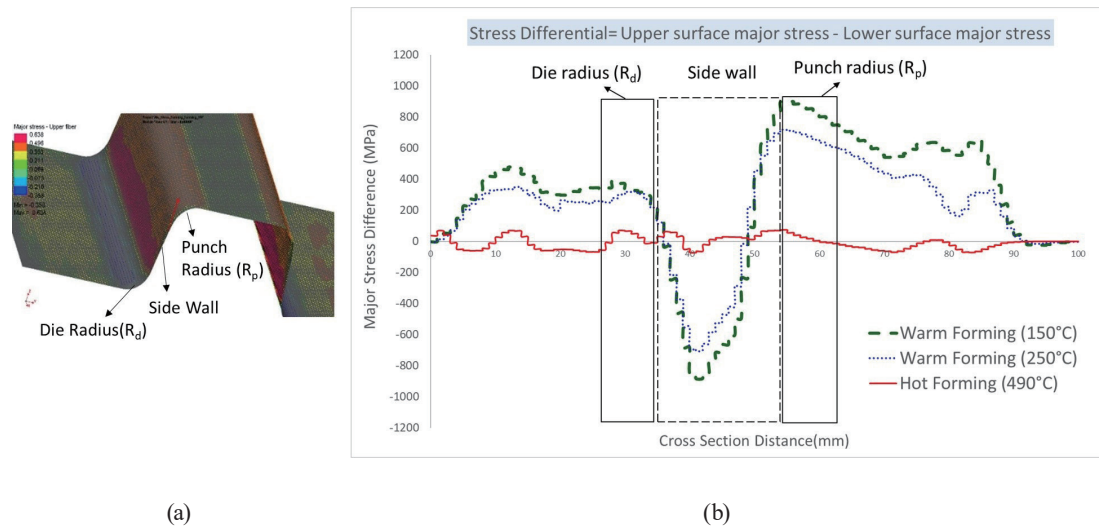


Fig. 6. (Color online) (a) Schematic illustration of die radius ( $R_d$ ), side wall, and punch radius ( $R_p$ ) and (b) stress differentials of parts under warm and hot forming conditions.

To further investigate the relationship between the stress differential and the magnitude of the springback angle, the total absolute stress differential was introduced in this study, calculated using the data in Fig. 4. The absolute values of the stress differentials were summed to prevent positive and negative values from canceling each other out, which could otherwise lead to a misinterpretation of the overall internal bending moment. The total absolute stress differential ( $S_{total}$ ) is calculated by summing the absolute differences between the major stresses on the upper and lower surfaces at each corresponding node along the defined cross section path. The mathematical expression is

$$S_{total} = \sum_{i=1}^n |\sigma_{upper,i} - \sigma_{lower,i}|, \quad (1)$$

where  $\sigma_{upper,i}$  and  $\sigma_{lower,i}$  represent the major stress (MPa) at the  $i$ -th node on the upper and lower surfaces, respectively. The summation range is along the 100 mm cross section distance, covering the die radius ( $R_d$ ), side wall, and punch radius ( $R_p$ ) zones. The resulting total stress differentials and their corresponding springback angles are presented in Fig. 7. The simulation results reveal a strong positive correlation between the total absolute stress differential and the springback angle. Specifically, the total stress differentials for warm forming at 150 and 250 °C, and hot forming at 490 °C were 44335, 27682, and 6687 MPa, respectively, with corresponding simulated springback angles of 10.1, 7.5, and  $-0.5^\circ$ . The predicted springback trends align well with the experimental measurements, confirming the reliability of the numerical model for stress analysis and springback prediction.

The simulation results suggest that in practical product development, surface stress differentials should be minimized through optimized tool designs and process parameters to

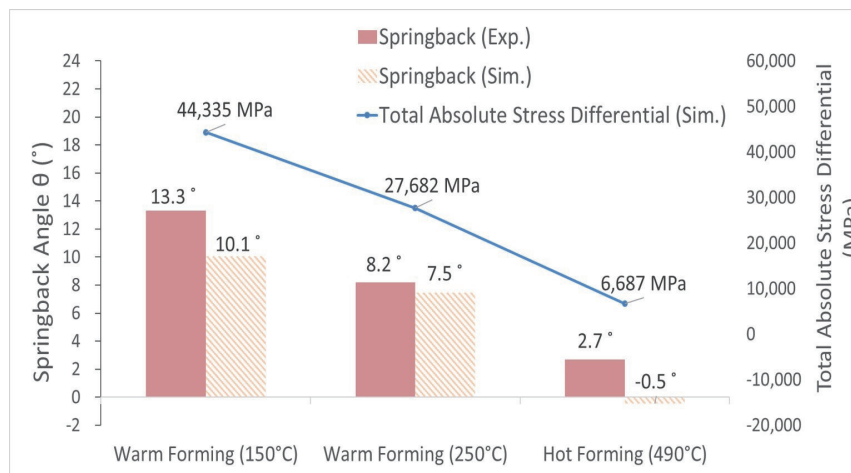


Fig. 7. (Color online) Correlation between total absolute stress differentials and springback angles under warm and hot forming conditions.

mitigate springback and enhance dimensional accuracy. Given that warm and hot forming involve complex thermomechanical coupling, the required temperature-dependent input parameters are significantly more intricate than those for conventional cold stamping, thereby increasing the difficulty in predicting springback. The numerical model established in this study demonstrates reliable predictive capability, aligning well with experimental trends. Accordingly, this model can be effectively utilized to meet the practical engineering requirements for die design and springback estimation of high-strength aluminum alloys.

#### 4. Conclusions

In this study, we investigated the springback characteristics of 7075 high-strength aluminum alloy during warm and hot forming processes through a combination of experimental measurements and numerical simulations. The results demonstrate that hot forming at 490 °C significantly reduces springback compared with warm forming, with the springback magnitude further decreasing as the warm forming temperature increases from 150 to 250 °C. A critical mechanical insight gained from this work is that the total absolute stress differential ( $S_{total}$ ), which is derived from the through-thickness stress distribution, exhibits a clear positive correlation with the final springback angle. This correlation provides a robust mechanical explanation for the improved dimensional accuracy observed at higher forming temperatures. The numerical model developed in this work demonstrates sufficient predictive capability for engineering applications, offering a valuable framework for utilizing the stress-based indicator ( $S_{total}$ ) as a computational sensor to potentially monitor and control springback during the forming of high-strength aluminum alloys at elevated temperatures.

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