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ORIGINAL ARTICLE

# Springback analysis of AA5754 after hot stamping: experiments and FE modelling

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**Abstract** In this paper, the springback of the aluminium alloy AA5754 under hot stamping conditions was characterised under stretch and pure bending conditions. It was found that elevated temperature stamping was beneficial for springback reduction, particularly when using hot dies. Using cold dies, the flange springback angle decreased by 9.7 % when the blank temperature was increased from 20 to 450 °C, compared to the 44.1 % springback reduction when hot dies were used. Various other forming conditions were also tested, the results of which were used to verify finite element (FE) simulations of the processes in order to consolidate the knowledge of springback. By analysing the tangential stress distributions along the formed part in the FE models, it was found that the springback angle is a linear function of the average through-thickness stress gradient, regardless of the forming conditions used.

**Keywords** Springback · Warm stamping · Hot stamping · Stretch bending · Pure bending · Aluminium alloy AA5754

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## 1 Introduction

In recent years, the automotive industry has been facing tough challenges associated with the need to improve fuel economy and reduce $CO_2$ emissions, due to more stringent environmental regulations. These demands have sparked a surge in the usage of lightweight materials, such as aluminium alloys, to replace traditional steels. Previous studies revealed that this replacement could achieve a direct vehicle weight reduction of up to approximately 47 % without compromising on performance [1]. However, it is difficult to form complex shaped parts at cold forming conditions using high-strength aluminium alloys due to their poor formability and excessive springback, which limits their application. These issues could be overcome by warm and hot stamping processes [2–11].

In the warm stamping process, an aluminium component is formed at an elevated temperature, normally below its recrystallization temperature, to achieve better formability. This technology has been studied for many years [4, 12], and it was found that the formability of aluminium alloys can be enhanced considerably to a level equivalent to that of mild steel, with a moderate increase in the forming temperature to the range of 150–350 °C. To enhance formability, warm forming processes are usually conducted under isothermal conditions and thus the forming tools are also heated up to a temperature ranging from 150 to 350 °C. Most recently, several studies have demonstrated that partial heating of the blank holder or die could achieve better formability due to the temperature gradient generated within the workpiece [5]. Although warm forming technologies can enhance formability, there is a potential risk that the forming process may destroy the desirable microstructure of an alloy and thus reduce the post-formed strength.

Most recently, a novel hot stamping process, solution Heat treatment, Forming and in-die Quenching technology

(HFQ®) has been developed [13, 14]. This process combines forming and heat treatment in one operation. Therefore, complex shaped components can be formed, while retaining the full mechanical strength of the alloy. Previous experimental evidence has shown that warm and hot stamping technologies are effective approaches to enhance formability; in addition, they are beneficial to springback reduction. However, springback under hot stamping conditions has yet to be characterised.

Springback is a shape discrepancy in the formed component between the fully loaded and unloaded configurations that can lead to misalignment in the assembly process. In past years, much research work has been conducted to study the effects of forming parameters (e.g. forming temperature, punch speed, die clearance/gap and die corner radius) on springback behaviour. Keum and Han [15] measured springback by performing draw bending tests for aluminium alloys AA1050 and AA5052 at different temperatures. It was found that springback decreased with increasing forming temperature, especially for forming temperatures above 150 °C. Moon et al. [16] demonstrated that the combination of a hot die (200 °C), cold punch (−10 °C) and low punch speed (1 mm/s) could reduce springback by up to 20 %. Laurent et al. [12] studied the mechanical behaviour and springback of AA5754-O under warm forming conditions using cup drawing tests. They reported that the tangential stress in the cup wall was the main factor affecting springback. All these previous studies have revealed that springback decreased for warm forming conditions compared with that at room temperature.

The experiments and finite element (FE) simulation work conducted by Moon et al. [16] and Kim et al. [17] showed that springback increased with increasing punch/forming speed, therefore a slow forming rate was recommended to reduce springback for warm forming. The clearance/gap between the punch and die also directly affected the drawing force, which is crucial to springback reduction. Master and Roy studied the effect of die corner radius on springback [18], and they pointed out that a sharp die corner radius led to more plastic deformation and less springback, due to the tighter constraint of blank material within the die. In the U-shape bending tests performed by the Fraunhofer-Institution [19], the side wall region of the formed part ‘curled out’ for larger die corner radii (e.g. $R$ = 5 mm), corresponding to greater springback, and ‘curled in’ for very small die corner radii (e.g. $R$ = 1 mm).

Springback of aluminium alloys has previously been predominantly studied for cold and warm forming conditions, but springback at higher temperatures, particularly for HFQ forming conditions, is not fully understood yet. The aim of this research is to characterise springback after stretch bending of aluminium alloy AA5754 hot stamped under various conditions. Comprehensive studies of the effects of punch speed, die gap and die corner radius on springback were conducted using both stretch bending and pure bending tests. Additionally, the effect of blank and tool temperature on springback in pure bending was investigated. The results of all these tests were used to verify FE simulations developed for the processes. These simulations were subsequently used to analyse the mechanics of springback under various forming conditions, and to establish a general relationship between the through-thickness tangential stress gradient along a formed part and the springback angle.

## 2 Experimental details

Tests were performed on a commercial aluminium alloy AA5754, supplied by Novelis UK Ltd. in the H111 condition with the rolling direction transverse to the longitudinal direction of the specimens, following the industry standard [20]. The composition of the material is shown in Table 1.

Stretch bending tests were used to study springback of AA5754 arising after hot stamping, using a cold and hot die/punch, and were carried out with a U-shaped bending test tool. 1000 and 250-kN presses were used to perform the U-shape and L-shape bending tests respectively as shown in Fig. 1.

Table 2 describes all the forming parameters used in this study. The effect of high forming speeds, characteristic of hot stamping processes such as HFQ, was also investigated [22, 23]. In the cold die/punch tests, the aluminium blank was heated by the furnace to 70 °C above the target temperature to allow for the temperature drop during transfer. A thermocouple was used to monitor the temperature of the blank. Once the target temperature was reached, the blank was removed from the furnace and transferred to the forming tool and formed quickly by cold dies. The formed blank was quenched for 10 s after stamping by holding it within the die cavity at a constant die closing force (DCF) of 180 kN. The formed blank was then removed from the die to allow further cooling in air to room temperature. For the hot die/punch tests, the temperatures of both the die and the punch were maintained at 150 °C using embedded electric cartridge heaters, and the formed blank was also held in the tools for 10 s after stamping with a DCF of 180 kN, before cooling in air. Simple bending tests, using an L-shaped bending tool, were conducted to investigate the effects of blank temperature, tooling temperature, die gap and die corner radius on springback.

**Table 1** The chemical composition of AA5754 [21]

| Element | Si | Fe | Cu | Mn | Mg | Cr | Zn | Ti | Al |
|---|---|---|---|---|---|---|---|---|---|
| Wt% | 0.08 | 0.16 | 0.004 | 0.45 | 3.2 | 0.001 | 0.01 | 0.02 | Bal. |

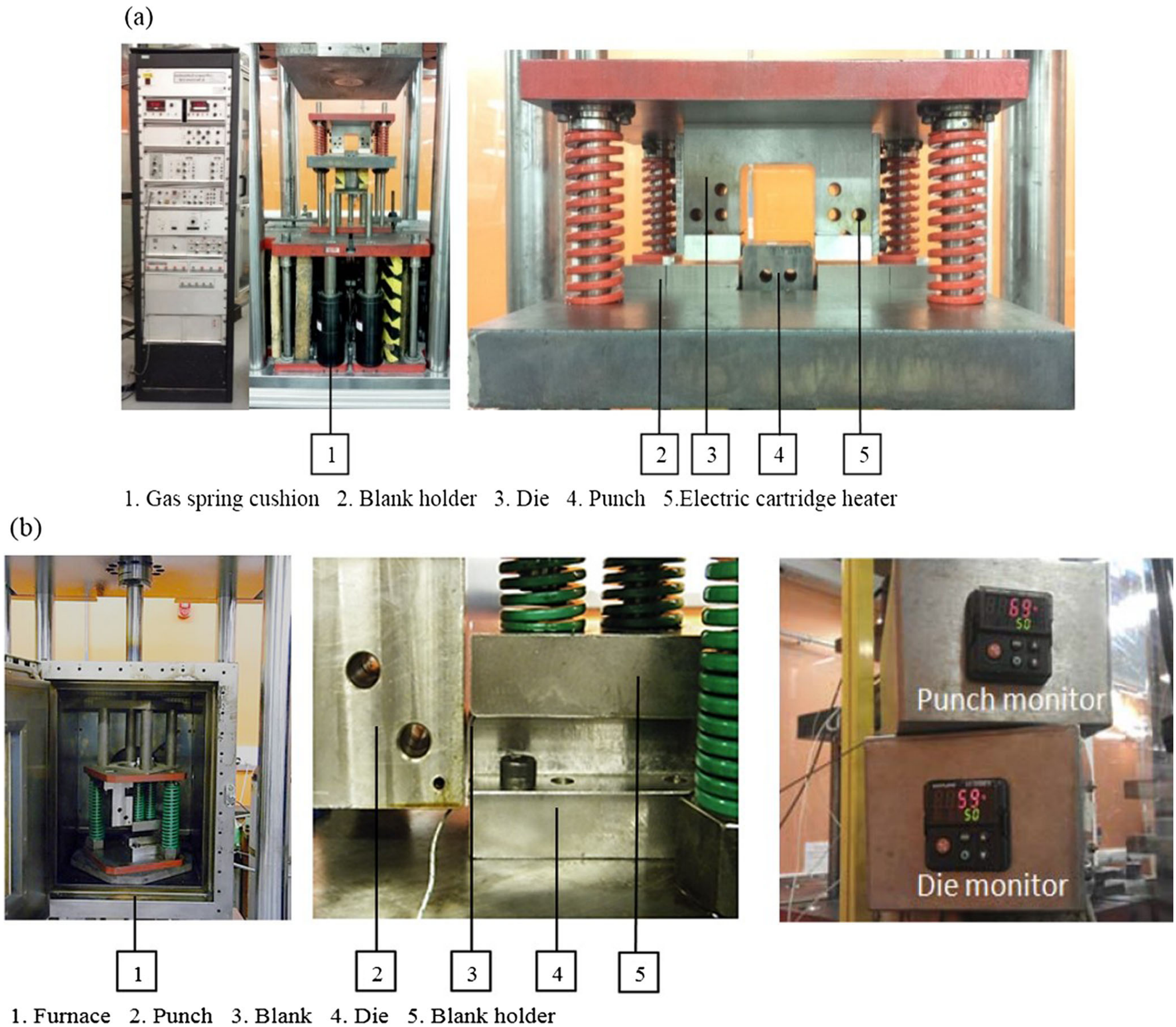



**Fig. 1** Diagram of the experimental set-ups: **a** U-shape bending and **b** L-shape bending

The geometries of the formed components are shown schematically in Fig. 2a, b. For simplicity, the tooling temperature ($T_{tooling}$) refers to the temperature of both the die and the punch. Springback in the U-shape bending part in which the side walls were nominally vertical and the flanges horizontal was characterised by two angles defined in Fig. 2a; the angle ($\theta_A$) between the vertical line and tangential line of the side wall represents the side wall curl, and the angle ($\theta_B$) between the horizontal line and flange denotes the flange springback. Points A, B, C and D were located on the formed part according to their curvilinear distance from 'O' measured from the inner surface of the die. Springback in the L-shape bending part was characterised by $\theta_A$, the angle between the vertical line and tangential line of the flange, as shown in Fig. 2b. Examples of formed U-shaped and L-shaped specimens are shown in Fig. 3.

## 3 Details of the FE simulation

The U-shape and L-shape bending processes were simulated using 3D finite element (FE) models developed with the commercial FE software PAM-STAMP, in the coupled temperature-displacement deformation mode. Schematic diagrams of the FE models used are shown in Fig. 4. For the U-shape bending simulation, a symmetry plane was used to reduce computational requirements.

The blank was modelled as an elasto-plastic object, and quadrilateral shell elements were assigned with a minimum element size of 1.6 mm. The viscoplastic behaviour of AA5754 at elevated temperatures was characterised by uniaxial tensile tests at 20, 200, 300 and 480 °C and at strain rates of 0.001, 0.1 and 1 $s^{-1}$. Figure 5 shows the flow stress curves of AA5754 as a function of temperature and strain rate in the

**Table 2** Forming parameters for U-shape bending and L-shape bending tests

| Forming parameters | U-shape bending | L-shape bending |
|---|---|---|
| Blank dimensions ($mm^3$) | 240 ×80×1.5 | 150×50×1.5 |
| Die corner radius (mm) | 5 | 4, 8 |
| Punch corner radius (mm) | 5 | 6.65 |
| Punch stroke (mm) | 70 | 50 |
| Initial blank temperature (°C) | 20, 150, 250, 350, 450 | 20, 150, 250 |
| Die and punch (tooling) temperature (°C) | 20, 150 | 20, 150 |
| Blank holder temperature (°C) | 20 | 20 |
| Die gap/blank thickness ratio | 1.1 | 1.1, 1.2, 1.3 |
| Punch speed (mm/s) | 75, 150, 300 | 75 |
| Blank-holding force (kN) | 20 | 1.5 |
| Die closing force (kN) | 180 | N/A |
| Quenching time (s) | 10 | 10 |
| Lubricant | WISURA ZO 3373 | |

plastic regime; these curves were input to PAM-STAMP as discrete data points.

For simplicity, the tools were assumed to be rigid bodies and meshed with four node shell elements, with an average element size of 2 mm. Tooling distortion due to loading/unloading and temperature changes was neglected. In the present research, a constant friction coefficient of 0.15 was used in the FE simulations to represent the full film lubrication conditions at the workpiece/tooling interfaces [24]. The heat transfer coefficient was defined as a function of the workpiece-tooling gap and the contact pressure [25]. The physical properties used in the FE analysis are shown in Table 3.

As shown in Fig. 6a, the FE simulation of the U-shape bending was performed in four distinct stages. In the holding stage, a uniform temperature was assigned to each component. The top blank holder moved downward and made contact with the blank to apply a constant blank-holding force (BHF) of 20 kN. In the stamping stage, the blank was drawn into the die cavity by the punch at a constant speed. In the quenching stage, the formed part was held within the die cavity for 10 s with a constant DCF of 180 kN. During the stamping and quenching stages, the blank temperature dropped dramatically due to the heat transfer between the blank and the tool; in the meanwhile, the tool temperature changed correspondingly. In the springback stage, springback was simulated using a 'One Step Springback' unloading scheme [27], which removes all the constraints simultaneously and forces the blank to attain equilibrium within two numerical increments.

The simulation of L-shape bending was performed in four distinct stages, as shown in Fig. 6b. In the holding stage, the blank was held between the blank holder and the die by a BHF of 1.5 kN. In the stamping stage, the blank was bent by the punch at a constant forming speed, and in the quenching stage, the formed part was held within the dies for 10 s. In both stages, heat transfer took place between the workpiece and the tool. In the final stage, springback was simulated using a 'One Step Springback' unloading scheme [27].

## 4 Results and discussion

### 4.1 Springback after stretch bending

#### *4.1.1 Springback of U-shaped test-piece under hot stamping conditions*

Figure 7 shows the effects of the initial blank temperature on springback for the cold die/punch forming condition. It can be seen that the springback angles decreased with increasing initial blank temperature up to 450 °C, which is the temperature that would be used for HFQ forming of AA5754 [22]. Good agreement between the experimental and FE simulation results have been achieved.

For springback angle $\theta_A$, the magnitude gently decreased by 15.7 % from 11.9 to 10.0° as the initial blank temperature ($T_{blank}$) was increased from 20 to 450 °C. The springback angle $\theta_B$ shows a similar trend to that of angle $\theta_A$, which decreased by 9.7 % from 15.3 to 13.8° as the blank temperature was increased from 20 to 450 °C. The FE simulation

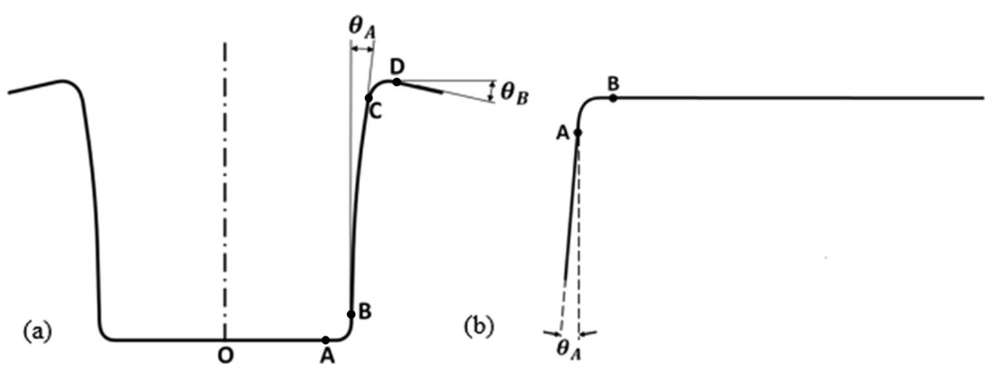



**Fig. 2** Angles defining springback for **a** U-shape bending and **b** L-shape bending

**Fig. 3** Example of formed U-shaped and L-shaped specimens

results were in good agreement with the experimental measurements for both springback angles $\theta_A$ and $\theta_B$ with errors less than 6 %.

Figure 8 shows the effect of initial blank temperature on springback at the hot die/punch forming condition, from the results of both the experiments and FE simulations, which had good agreement.

The springback angles $\theta_A$ and $\theta_B$ reduced with increasing initial blank temperature for the hot die/punch forming condition ($T_{tooling}$ = 150 °C), which is the same trend observed for the cold forming condition. However, for the hot die/punch forming condition, springback was more sensitive to the initial blank temperature. According to the experimental measurements, the springback angle $\theta_A$ decreased by 57.1 % from

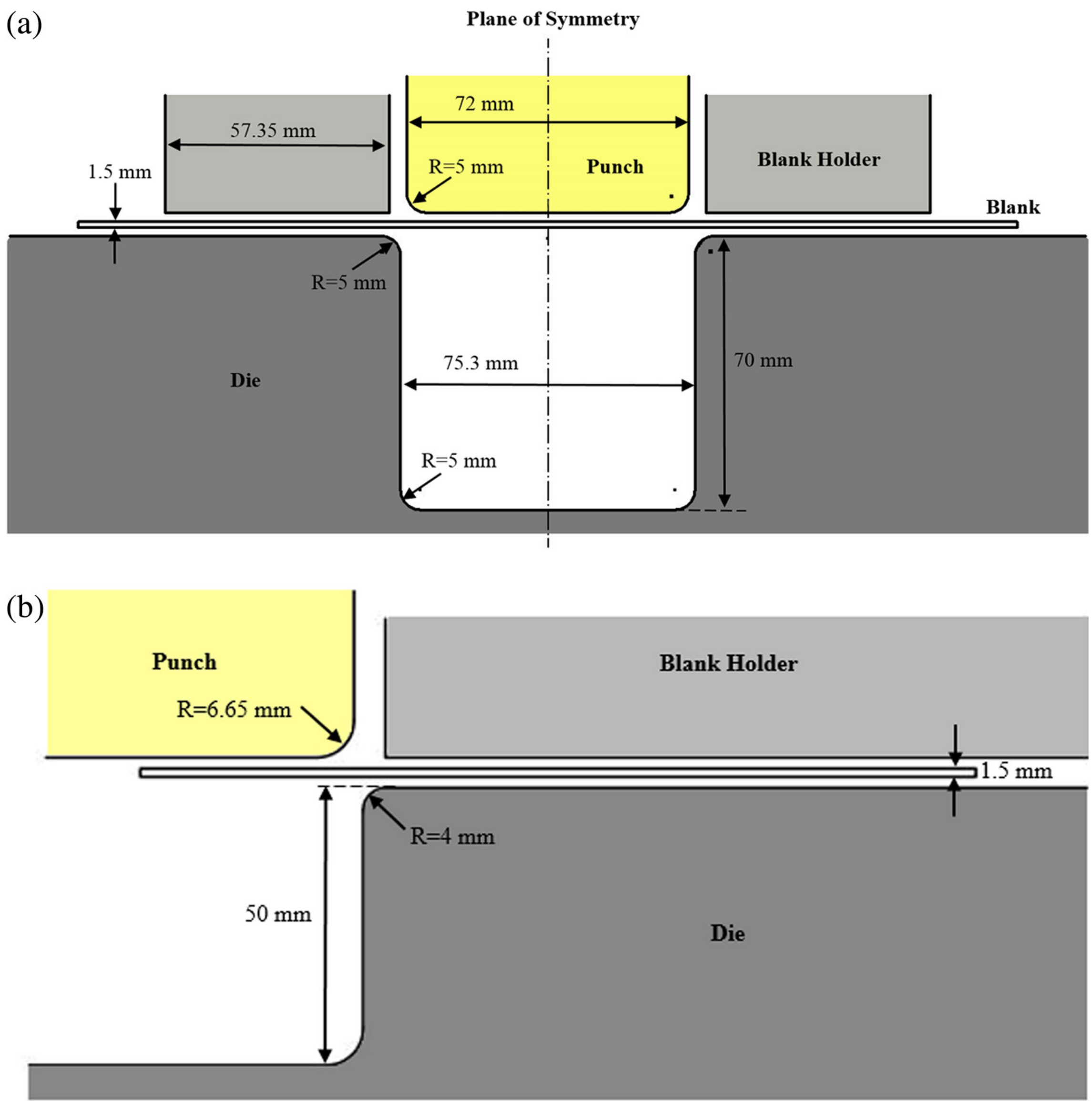



**Fig. 4** Schematic diagram of the FE model for **a** the U-shape bending tests and **b** the L-shape bending tests

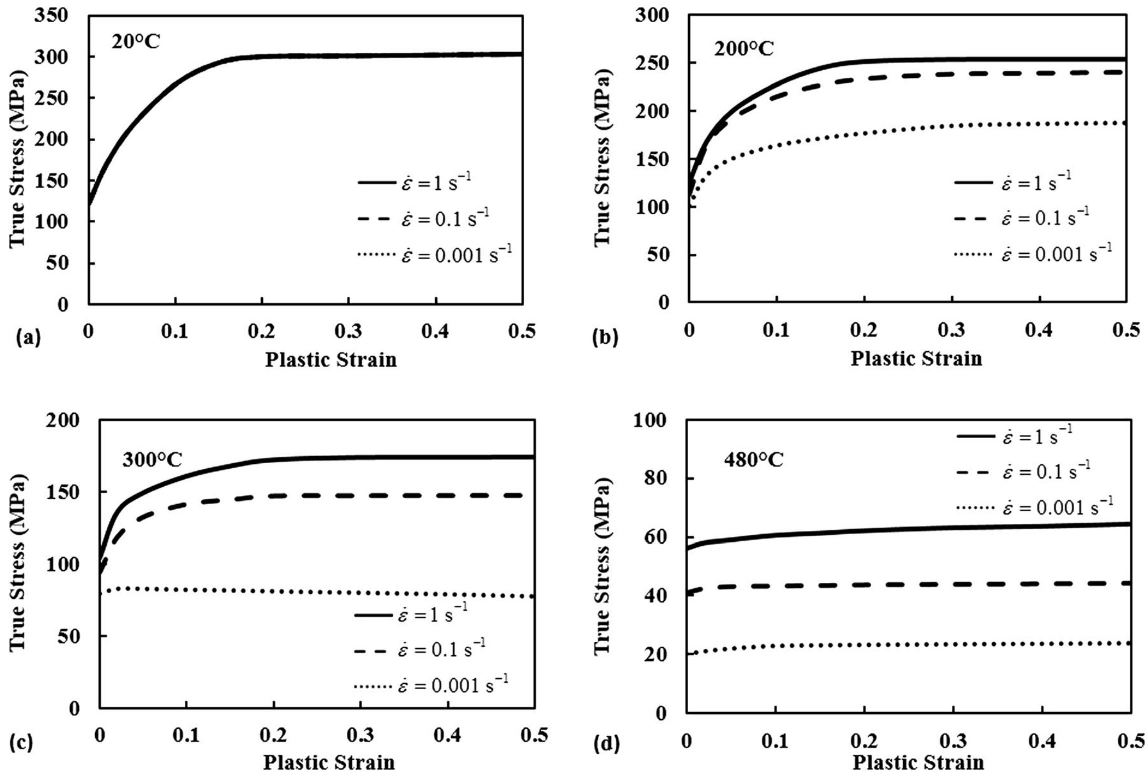



**Fig. 5** True stress-strain curves of AA5754 at **a** 20 °C, **b** 200 °C, **c** 300 °C and **d** 480 °C

9.9 to 4.2°, whereas the angle $\theta_B$ was reduced by 44.1 % from 12.6 to 7.0°, as the blank temperature was increased from 150 to 450 °C. It could therefore be deduced that a combination of a high initial blank temperature and hot die/punch for forming would be beneficial for minimising springback.

It has been shown previously that the difference between the tangential stress distributions across the top and bottom layers of a formed blank influences the level of springback [17]. The larger the tangential stress gradient through the thickness of the blank, the greater the springback. These stress distributions were therefore obtained from the verified FE simulation results to explain the decrease in the springback angle for hot stamping conditions.

Figure 9 shows tangential stress distributions along the top and bottom layers of the formed part at the end of the quenching stage of the FE simulation for the cold die/punch tests. The section was divided into four regions to analyse the factors affecting springback.

For the cold forming condition, the high strength and material draw-in from the blank holding areas resulted in excessive blank material in region OA, the punch bottom region, causing rippling and distortion of the blank here, and preventing the die from becoming fully closed. Therefore, alternating stress states could be observed in this region. For the hot forming condition ($T_{\text{blank}}$ = 450 °C and $T_{\text{tooling}}$ = 20 °C), the stresses in both the top and bottom layers were in tension. At elevated temperatures, the strength of the blank material decreased, subsequently reducing draw-in from the blank holding areas, and increasing the tensile deformation in this region. In region AB, the punch corner region, the blank was subject to a compressive stress in the upper layer and a tensile stress in the lower layer for the cold forming condition. However, when the blank temperature was increased to 450 °C, a transition from tension to compression in the upper layer and a transition from compression to tension in the lower layer took place in this region due to the combined effects of plastic stretching and bending over the punch corner. In region BC, the sidewall region, the blank material experienced bending, unbending and reverse bending during the forming process, i.e. the blank was bent while it was drawn into the die cavity from the CD region and it was straightened by the side wall of the die in region BC. This resulted in tensile stresses in the lower layer and compressive stresses in the

**Table 3** Material properties of blank and tools [17, 26]

| Property | AA5754 | Tool steel |
|---|---|---|
| Thermal conductivity (kW/mm·K) | 140 | 20 |
| Specific heat (mJ/t·K) | 960E6 | 650E6 |
| Density (t/mm$^3$) | 2.9E-9 | 7.8E-9 |
| Poisson's ratio | 0.34 | 0.3 |
| Young's modulus (GPa) | 70 | 210 |
| Dissipation factor | 0.9 | 0.9 |
| Dilatation coefficient (at 20 °C) | 5E-5 | – |
| Friction coefficient | 0.15 | |

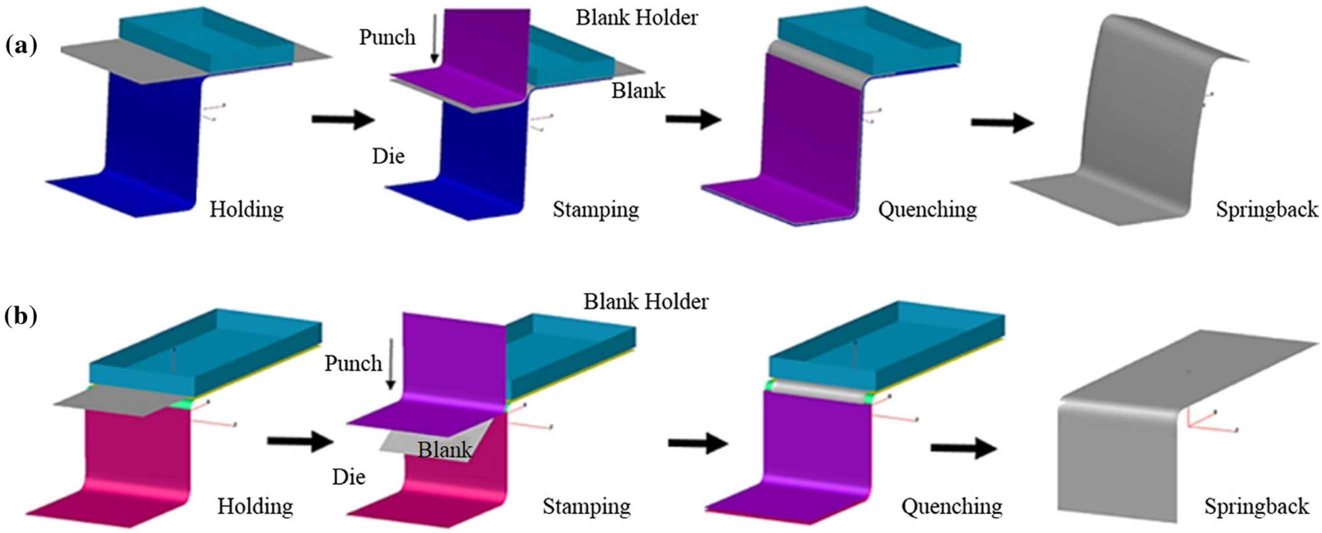


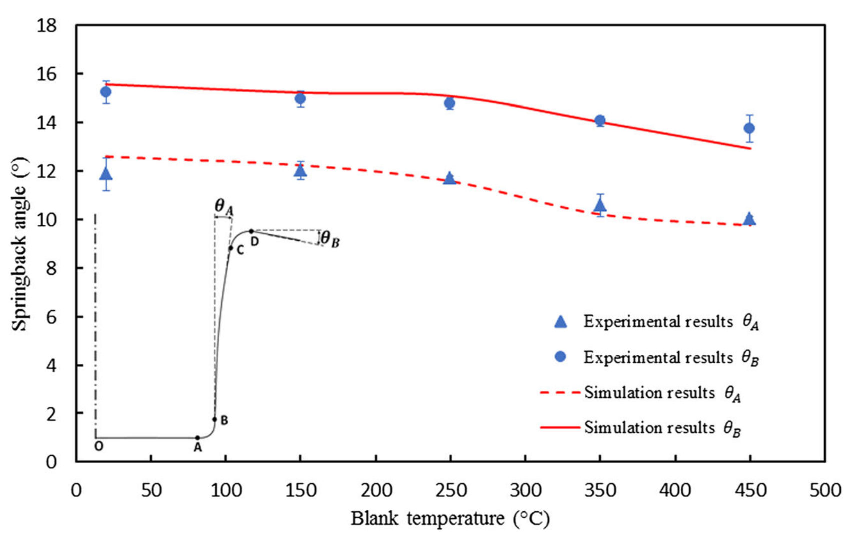

**Figure 6** The multi-stage FE simulation schemes for the **a** U-shape and **b** L-shape bending processes

upper layer. This stress distribution created a large bending moment, and therefore a large amount of springback in this region; this was observed in common with the findings reported in [17]. At 450 °C, the tangential stress gradients between the top and bottom layers of the blank decreased, except at the entry and exit to this region where there was higher plastic stretching at the punch and die corners. Hence, a reduction in the amount of springback could be achieved at elevated blank temperatures. The stress distributions for different blank temperatures were similar in region CD, the die corner region. The stresses changed from tension to compression in the lower layer and compression to tension in the upper layer. This was caused by the bending of the blank material taking place at the exit to this region (point D), and the reverse bending of the material in the side wall at the entry to this region (point C). As expected, the stress level at point C was greater at 450 °C; this was due to the lower drawability and hence higher plastic straining at the die corner, leading to a higher stress level after quenching.

The reduction in the average through-thickness tangential stress gradient along the formed part at a temperature of 450 °C resulted in a lower level of springback. A similar analysis was also carried out on the results of the hot die/punch tests. Tangential stress distributions along the upper and lower layers of the formed part are plotted and shown in Fig. 10. The strength of the blank material decreased for the hot die/punch forming condition, and consequently a reduction in the overall stress level was observed compared to that of the cold die/punch forming conditions. The stress distributions in the formed part showed similar trends to the cold die/punch forming condition. However, an obvious difference was noted at 450 °C; the material in some locations in the side wall region BC was subject to a tensile stress in the upper layer and compressive stress in the lower layer, as shown in Fig. 10.

This was due to the reverse bending effect (a similar effect was also found in [17]), which becomes more significant at elevated temperatures when the material strength is lower. The lower through-thickness tangential stress gradients that result

**Fig. 7** Comparisons between the FE simulation and the U-shape bending test results at different initial blank temperatures ($T_{tooling}$ = 20 °C)



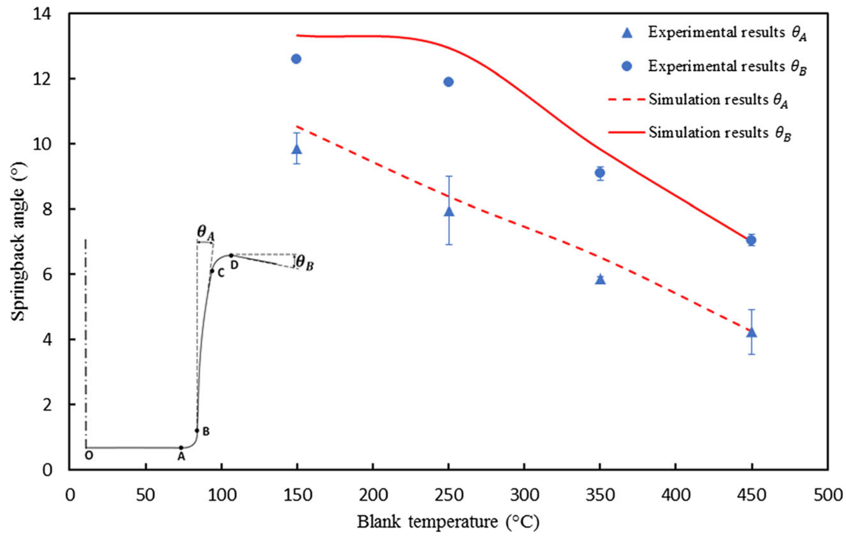



**Fig. 8** Comparisons between the FE simulation and the U-shape bending test results at different initial blank temperatures ($T_{tooling}$ = 150 °C)

leads to further reduced side wall curvature and hence springback. In summary, springback greatly decreased for hot stamping conditions, particularly when a hot die/punch was used, due to the significantly reduced stress level and hence overall lower through-thickness stress gradient along the formed part.

*4.1.2 Springback at high forming speeds*

Figure 11 shows that punch speed also played a dominant role in springback; as punch speed was increased, springback angles $\theta_A$ and $\theta_B$ were significantly decreased for the hot die/punch forming condition for $T_{blank}$ = 250 °C. The punch speed investigated in this study was much faster than previous studies (≥75 mm/s compared with 0.5–1 mm/s) [12, 17]. In the case of angle $\theta_A$, it was found that it decreased by 55.9 % from 7.9° at 75 mm/s to 3.5° at 300 mm/s. The angle $\theta_B$ also showed a considerable reduction of 37.6 % from 11.9 to 7.4°. In addition, a consistent difference between $\theta_A$ and $\theta_B$ of about 3.5° was found from the experimental results. Although the higher punch speed decreased the side wall curvature, the shape of the blank flange remained almost unchanged. The FE prediction was in good agreement with the experimental measurements for both springback angles $\theta_A$ and $\theta_B$ with errors of less than 8 %.

To further investigate the springback phenomenon, the tangential stress distribution at three punch speeds was plotted in Fig. 12. The stress distributions in the punch bottom and die corner regions (OA and CD) were almost identical for the three punch speeds, suggesting that significant material drawing was already occurring at the selected test speeds, limiting the extent of plastic deformation in these regions. This is due to the higher material strength attained from strain rate hardening. In region BC, the higher punch speeds and hence

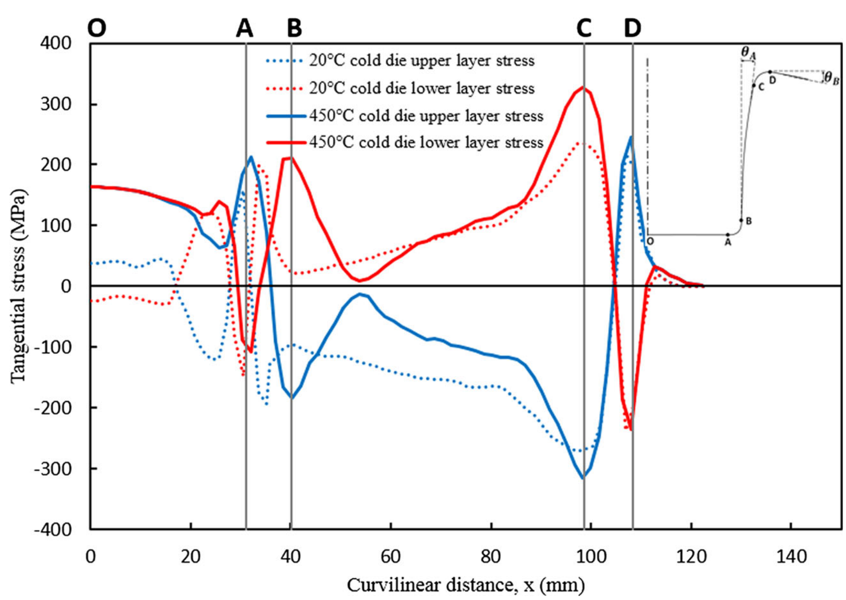



**Fig. 9** Tangential stress distributions on the top and bottom layers of the formed part for the cold die/punch forming condition ($T_{tooling}$ = 20 °C, $\mu$ = 0.15, BHF = 20 kN, DCF = 180 kN, $v$ = 75 mm/s) for $T_{blank}$ = 20 °C and $T_{blank}$ = 450 °C U-shape bending

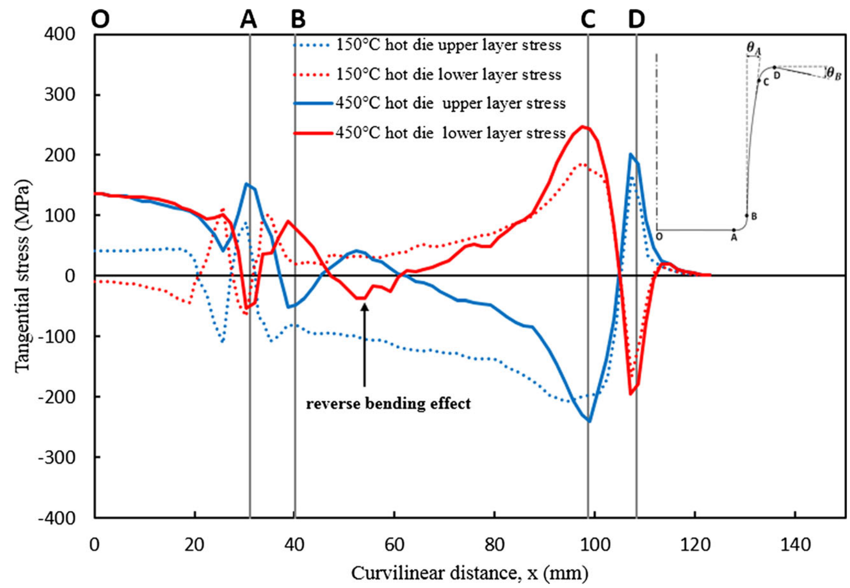



**Fig. 10** Tangential stress distributions on the top and bottom layers of the formed part for the hot die/punch forming condition ($T_{tooling}$ = 150 °C, $\mu$ = 0.15, BHF = 20 kN, DCF = 180 kN, $v$ = 75 mm/s) for $T_{blank}$ = 150 °C and $T_{blank}$ = 450 °C

greater drawability resulted in a lower stress level in the side wall region, decreasing the side wall curvature and hence springback. Similarly, the stresses developed in region AB also decreased with increasing punch speed. Consequently, the overall through-thickness stress gradient of the formed part reduced. In summary, the high forming speeds characteristic of hot stamping processes would be beneficial for reducing springback in a formed component.

## 4.2 Springback after simple bending

### *4.2.1 Effect of temperature*

The trend of the effect of temperature on springback in L-shape bending tests was identical to that for the U-shape bending tests; higher blank and tooling temperatures decrease the required bending moment for a given curvature, resulting in lower springback after unloading. As shown in Fig. 13, the springback angle $\theta_A$ was on average reduced by 11.9 % when the tooling temperature increased from 20 to 150 °C. In the case of cold die/punch forming (die corner radius $R$ = 4 mm), it was observed that $\theta_A$ decreased by 66 % from 4.0° at $T_{blank}$ = 20 °C to 1.4° at $T_{blank}$ = 250 °C , while for the hot die/punch forming condition, this angle decreased by 66 % from 3.6 to 1.2° as the blank temperature increased. The sensitivity of springback to blank temperature was almost identical for both cold and hot die/punch forming conditions. The FE predictions were in good agreement with the experimental measurements with errors of less than 4 %.

Figure 14 shows the tangential stress distributions for two tooling temperatures ($T_{tooling}$ = 150 °C vs. $T_{tooling}$ = 20 °C ) at $T_{blank}$ = 250 °C . It can be seen that at the higher temperature, smaller tensile and compressive stresses were generated in the upper and lower layers of the blank respectively in the region

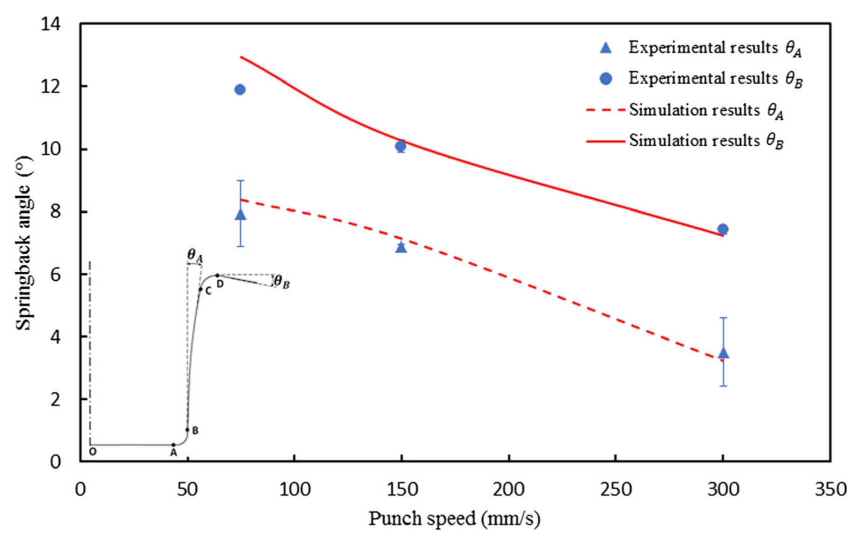



**Fig. 11** Comparisons between the FE simulation and the U-shape bending test results at varying punch speeds for the hot/die punch forming condition, for $T_{blank}$ = 250 °C and $T_{tooling}$ = 150 °C

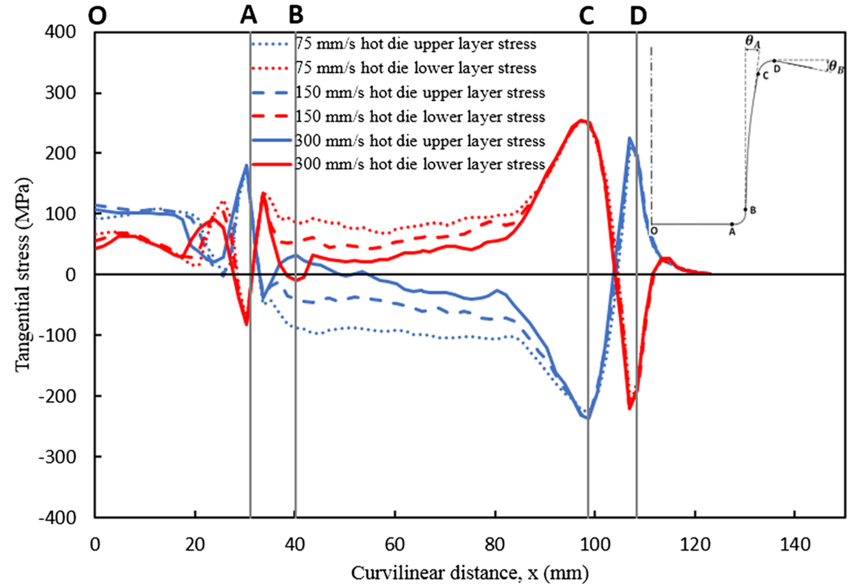



**Fig. 12** Tangential stress distributions on the top and bottom layers of the formed part for the hot die/punch forming condition ($T_{blank}$ = 250 °C, $T_{tooling}$ = 150 °C, $\mu$ = 0.15, BHF = 20 kN, DCF = 180 kN, $\nu$ = 75 mm/s) for three punch speeds 75, 150 and 300 mm/s

AB. As a result, the decreased through-thickness tangential stress gradients led to decreased springback at elevated tooling temperatures.

*4.2.2 Effect of die gap*

It was found that the springback angle $\theta_A$ gradually increased with increasing die gap, as shown in Fig. 15. With an 18 % increase in the value of die gap to blank thickness ratio, there was a 19 % increase in the value of springback angle from 4.0 to 4.8°. The experimental results also had a good agreement with the FE results, with errors of less than 5.4 %.

The trend of increasing springback with increasing die gap was in close agreement with the results from [28] and could be explained by the moment-curvature relationship. As the die gap increases, the curvature of the blank at the bend edge after forming increases. Hence, the bending moment required to achieve a given curvature increases, which corresponds to the increased springback. The stress distributions of the upper and lower layer of the blank are shown in Fig. 16 for two different die gaps.

It could be seen that the curvilinear distance over which the tangential stresses were acting increased for a larger die gap; the resulting increased overall through-thickness tangential stress gradient therefore led to increased springback. Hence, a smaller die gap would reduce springback and improve the dimensional accuracy of a formed part.

*4.2.3 Effect of die corner radius*

A comparison was made between the effect of two different die corner radii ($R$ = 4 mm and $R$ = 8 mm) at the cold die/

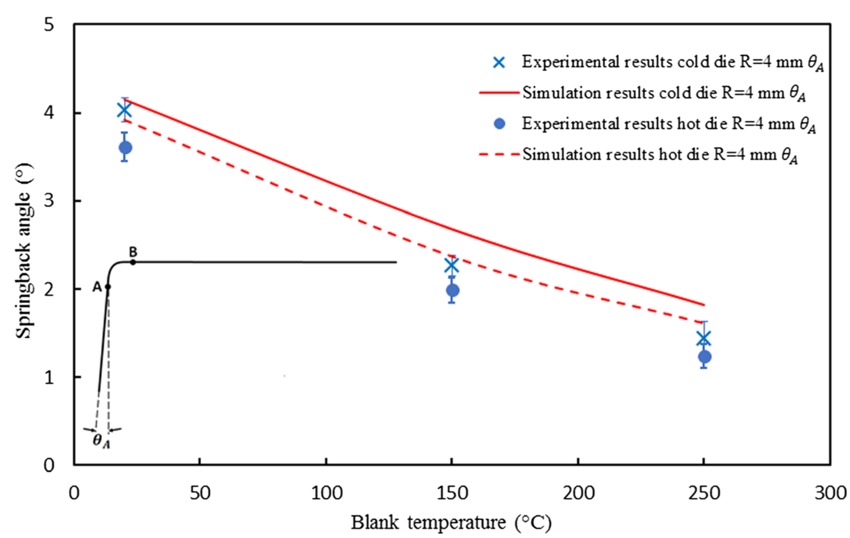



**Fig. 13** Comparisons between the FE simulation and the L-shape bending test results at different initial blank temperatures for the cold and hot die/punch forming conditions, with die corner radius $R$ = 4 mm, $\nu$ = 75 mm/$s$

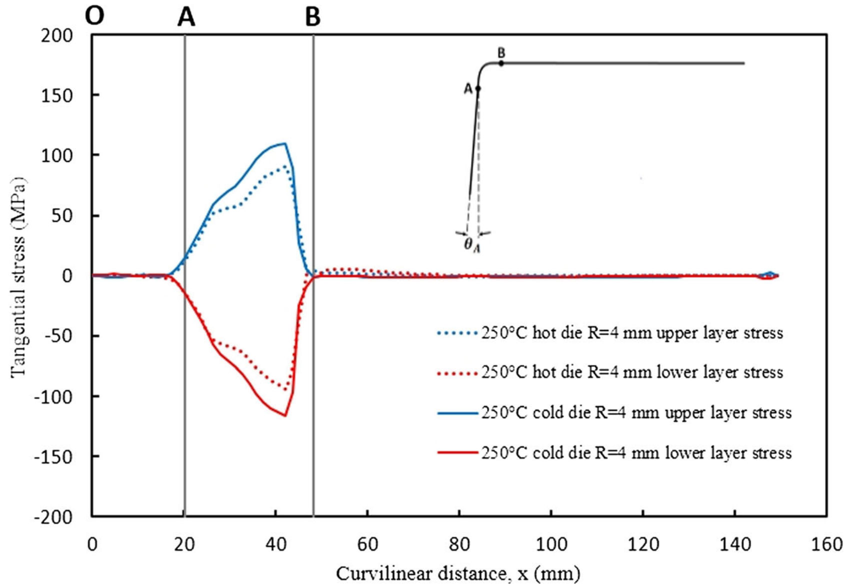



**Fig. 14** Tangential stress distributions on the top and bottom layers of the formed part for cold and hot die/punch forming conditions, with die corner radius $R$ = 4 mm ($T_{blank}$ = 250 °C, $\mu$ = 0.15, BHF = 1.5 kN, $\nu$ = 75 mm/s)

punch forming condition as shown in Fig. 17. It was found that a smaller die corner radius led to a smaller amount of springback due to the smaller required bending moment. The angle $\theta_A$ decreased by 20.3 % from 5.4 to 4.3° as the temperature increased from $T_{blank}$ = 20 °C to $T_{blank}$ = 250 °C in the case of $R$ = 8 mm. This angle decreased by 64.5 % from 4.0 to 1.4° for the same temperature increase in the case of $R$ = 4 mm. For comparison, an average 43.9 % decrease was achieved in the angle $\theta_A$ when the die corner radius decreased from $R$ = 8 mm to $R$ = 4 mm. The FE results were also within 4.8 % of the experimental results.

The experimental measurements obtained in this study were in close agreement with the work of other researchers [17]. The tangential stress distributions for two die corner radii in Fig. 18 explain the springback decrease. For the smaller die corner radius, the tangential stresses act over a smaller curvilinear distance in the die corner region AB, reducing the average through-thickness tangential stress gradient.

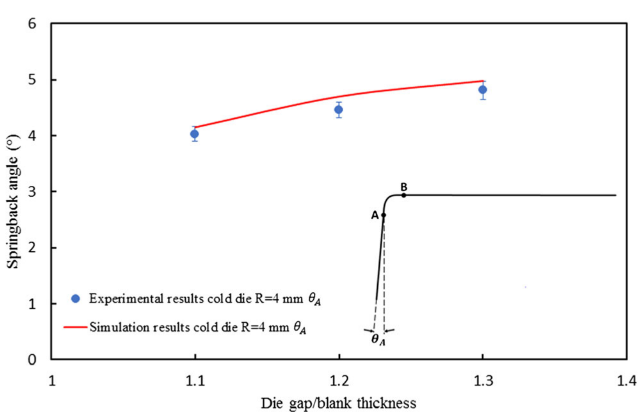



**Fig. 15** Comparisons between the FE simulation and the L-shape bending test results for cold forming condition for three die gaps ($g/t$ = 1.1, 1.2 and 1.3), $\nu$ = 75 mm/s

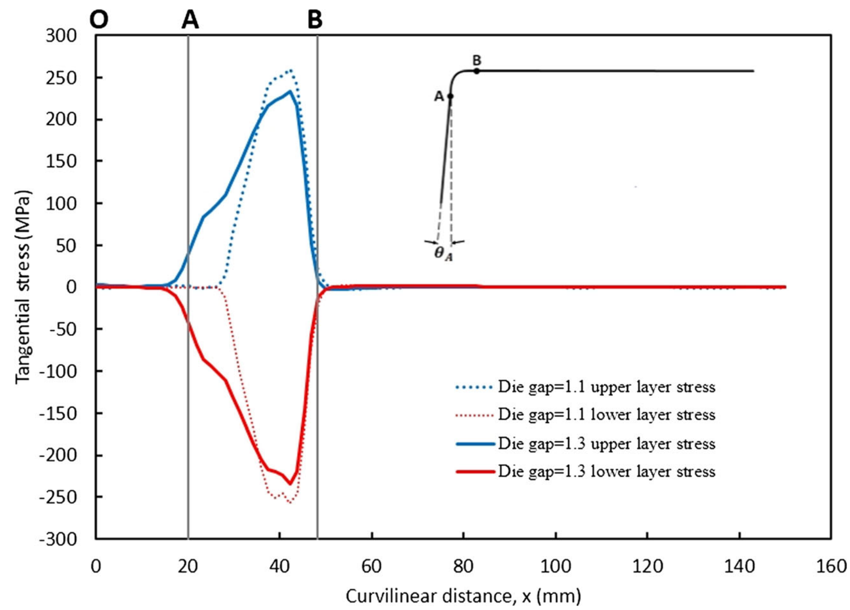
### 4.3 Through-thickness tangential stress gradient relationship

From the comprehensive analysis of springback under both stretch and pure bending conditions tested with a wide range of processing parameters and forming conditions, it was confirmed that the level of springback was closely related to the tangential stress distribution in the top and bottom surfaces of the blank after forming. The smaller the difference between the stresses in the top and bottom layers of the blank, i.e. the lower the through-thickness tangential stress gradient along the formed part, the lower the level of springback. This has previously been observed in the literature, and agrees with the theory of springback prediction.

Oliveria et al. [27] carried out FE simulations of U-shape bending of two steels: mild (DC06) and dual phase (DP600) steel. By analysing the through-thickness stress gradient for the material that flowed through the drawbead and the die radius using several work-hardening constitutive models, the study pointed out that smaller through-thickness stress gradients are usually associated with less springback. In addition, similar FE springback prediction work for AA5754-O found in Kim and Koç's paper suggests that as the difference between the tangential stresses on the top and bottom of the blank decreased, the springback reduced [17].

Springback is usually determined by the bending moment applied on the formed part, which is calculated by integrating the stresses through the part thickness; the larger the bending moment, the greater the springback [29]. However, the stress difference or through-thickness stress gradient can also give an indication of the bending moment and hence springback of the formed part. To consolidate this relationship between the stress gradient and the

**Fig. 16** Tangential stress distributions on the top and bottom layers of the formed part for the cold forming condition ($T_{tooling} = T_{blank} = 20$ °C, $\mu = 0.15$, BHF = 1.5 kN, v = 75 mm/s) for two die gaps




springback angle, all the test results were compiled into one plot as shown in Fig. 19. The stress gradient calculated from the FE simulation results of each forming condition along the same section of each component is defined in Eq. (1), where averages are defined by Eq. (2) and Eq. (3). The springback angle in Fig. 19 refers to $\theta_A$ in the L-shape bending tests and $\theta_B$ in the U-shape bending tests.

$$\text{stress gradient} = \frac{\text{average through-thickness stress difference}}{\text{average blank thickness}} \quad (1)$$

$$\text{average through-thickness stress difference} = \frac{\sum_i^n \sigma_{top,i} - \sum_i^n \sigma_{bottom,i}}{n} \quad (2)$$

$$\text{average blank thickness} = \frac{\sum_i^n t_i}{n} \quad (3)$$

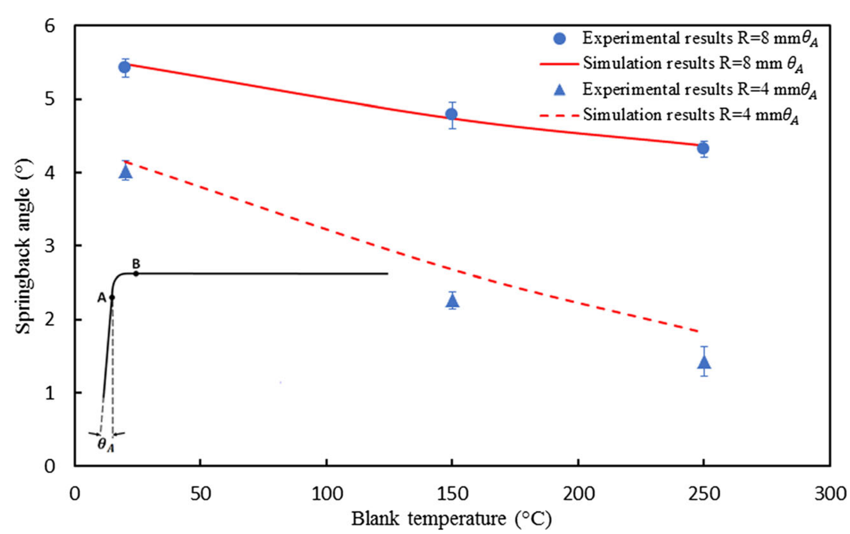
where $n$ = number of calculation points taken along the section of the component.

For AA5754, it was found that a linear relationship between the stress gradient and the springback angle existed regardless of the type of loading, blank geometry and forming conditions (e.g. blank temperatures, tooling temperatures, punch speeds, etc.). The line of best fit was found as shown in Eq. (4).

$$\text{springback angle} = 0.179 \times \text{stress gradient} \quad (4)$$

In summary, the springback phenomenon could be adequately explained by the average through-thickness tangential

**Fig. 17** Comparisons between the FE simulation and the L-shape bending test results at the cold die/punch forming conditions for two die corner radii $R = 4$ mm and $R = 8$ mm



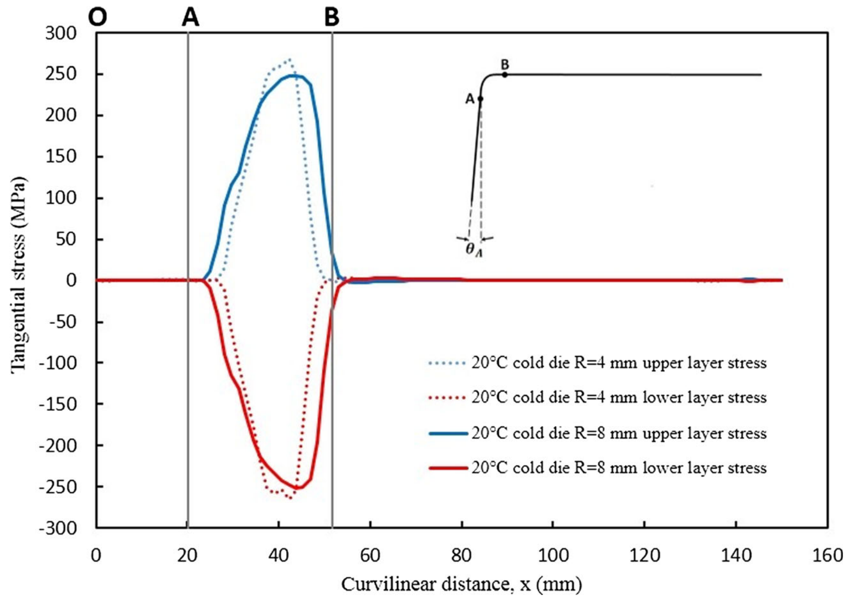



**Fig. 18** Tangential stress distributions on the top and bottom layers of the formed part at the cold forming condition ($T_{tooling}$ = 20 °C, $T_{blank}$ = 20 °C, $\mu$ = 0.15, BHF = 1.5 kN, $v$ = 75 mm/s) for the two die corner radii $R$ = 4 mm and $R$ = 8 mm

stress gradient; an increase in the stress gradient as calculated in Eq. (1) would lead to an increase in springback.

## 5 Conclusions

Springback under hot stamping conditions was successfully characterised using stretch bending tests, and it was found that higher blank and die temperatures reduced the amount of springback in a formed part. When the blank temperature was increased from 20 to 450 °C, the flange springback angle decreased by 9.7 % under the cold die condition, while for the hot die condition it decreased by 44.1 %. This was due to the overall reduced stress level in the blank. High forming speeds, an intrinsic feature of hot stamping processes, were also found to be beneficial for reducing springback.

Springback was also investigated under pure bending conditions, and the effect of blank and tooling temperature, die gap and die corner radius was determined. Elevated temperature forming, a smaller die gap and larger corner radius were all found to be beneficial for reducing springback.

FE models of the processes were developed and successfully validated using the experimental results. The relationship between the springback angle and the average through-thickness tangential stress gradient was consolidated by analysing the tangential stress distributions along the length of the formed parts and summarising all the results on a single plot. The linear relationship between them held regardless of the testing methods (U-shape or L-shape bending), blank geometry or processing parameters (e.g. blank temperatures, tooling temperatures, punch speeds etc.) used.

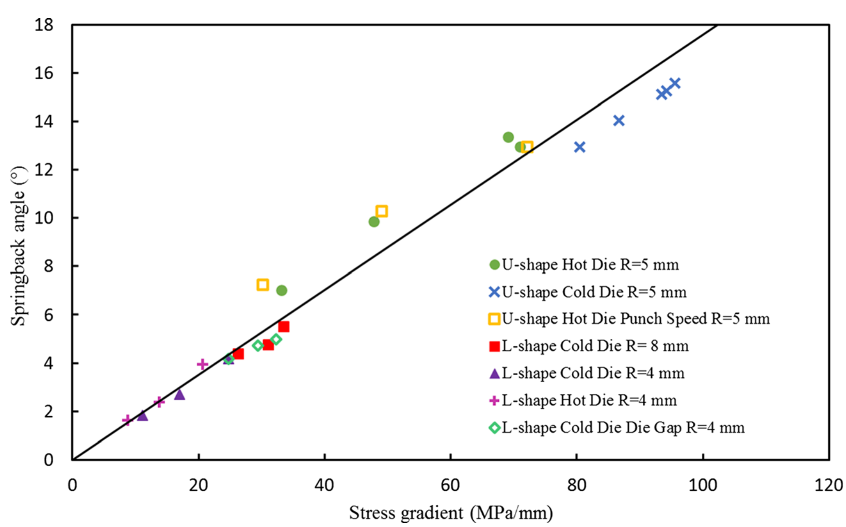



**Fig. 19** Relationship between the average through-thickness tangential stress gradient and springback angle

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