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TECHNICAL PAPER

Experimental, analytical and parametric evaluation of the springback behavior of MART1400 sheets

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Abstract
Due to high amount of springback behavior of MART steels, a large amount of time is wasted during the manufacturing of correct die setup for the intended products. Therefore, many sheet metal forming industries rely on the predicting ability of finite element analysis to reduce their forming costs. In this study, the effects of bending parameters on the springback behavior of MART1400 steel have been investigated by conducting V-bending tests with various die angles (30°, 60°, 90°, and 120°), punch radiuses (2 mm, 4 mm and 6 mm) and force holding times (0 s, 10 s). Furthermore, the predicting ability of different isotropic hardening models (Hollomon, Ghosh, Hocket-Sherby, Swift and Voce) coupled with the Von-Misses yield criterion on the springback behavior of MART1400 steels has been investigated. Additionally, the effect of applying a local heating around the bending area of MART steel on the springback behavior has been parametrically investigated. It has been found that increasing of die angle, and punch radius have resulted in an increase of springback, while a force holding time of 10 s has decreased the springback. Application of heat at 375 °C and 475 °C around the bending area of MART1400 has resulted in 40.18% and 55.13% reduction of springback due to the lowering of strain hardening.

Keywords V-bending · Isotropic hardening models · Springback · FEA · MART1400

1 Introduction

Due to the increased awareness on the environmental effects of global emissions and the strict regulations about fuel consumptions, many sheet metal forming industries have started to use or increase the use of Advanced High Strength Steels (AHSS) in their products [1]. The incredibly high strength levels that is achieved by AHSS have enabled to reduce the thickness of formed parts, which in return has enabled to substantially decrease the weights of parts while improving the strength [2]. The weight reduction that can be achieved with the AHSS has especially ushered new opportunities for automobile industry to lower the fuel consumptions and carbon emissions [3, 4]. Even though the high strength levels of these steels have enabled to significantly reduce the weight of parts, these high strength levels have also brought about the new challenges for sheet metal forming industries such as severe springback behaviors [5–9]. Springback behavior is commonly observed in many of the sheet metal forming methods such as tube bending, L-bending, U- bending, press bending, air bending and V-bending due to the elastic strains present in the material after the plastic deformation [10–19]. Problems arising due to the springback have been estimated to cause around $50 million cost per year due to delayed production, unqualified parts and etc. [20–22].

Due to these huge impacts of springback, many research studies have been conducted to understand the springback behavior of different AHSS or to reduce its adverse effects in the forming process by either estimating the degree of springback or reducing it by a variety of methods. Li et al. [5] have compared the twist springback of DP and TRIP steels. They have observed that the DP steel has exhibited higher springback than TRIP steels for the same strength level and concluded that the high initial strain hardening of

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DP steels as compared to TRIP steels has been the main reason for the higher springback in DP steels. Toros et al. [23] have investigated the capability of different yielding models such as Hill-48, Barlat-89 and YLD2000-2d on predicting the springback of V-bended TRIP800 steels. The authors have observed that the YLD2000-2d material model has had the best prediction of springback for TRIP800 steels. Concerning the change of elastic modulus with the applied strain Tiska and Lucacs [24] have conducted cyclic tension and compressions tests for DP600, DP800 and DP1000 steels in order to observe the change of elastic modulus of DP steels with the applied strain. The authors have found an apparent decreasing elastic modulus for each of the DP steels with the decreasing ratio DP600 > DP800 > DP1000. In some studies [25, 26], authors have conducted FEA by taking into consideration of the nonlinearity of elastic modulus in their models and observed a significant improvement of springback predictions. Ghaei et al. [25] have modified the Quasi Plastic Elastic (QPE) model in order to divide the total strain into elastic and plastic strains, while taking into account the linear and nonlinear unloading portions of the stress–strain curve and evaluated the accuracy of the model by forming a U-channel from a TRIP780 steel. In their results, authors, with the modified model, have been able to successfully predict the curl radius, wall angle and flange angle of the U-channel formed part. Chang et al. [26] have conducted numerical V-bending tests with different material models considering the constant elastic modulus and nonlinear elastic modulus of medium Mn third generation AHSS. The authors have concluded that the material model which considers the nonlinearity of elastic modulus during cyclic deformation has predicted the springback behavior with a higher accuracy as compared to the material model with constant elastic modulus In order to understand the mechanisms that causes twist springback especially in rail components, where the shape of the section varies along a curvature, Xue et al. [27] have formed a C-rail benchmark and analyzed the stress and moments on the part by utilizing FEA methods. The authors have found out that the unbalanced bending moments caused during forming operation has been the main cause of twist springback. In an attempt to minimize the twist springback in C-rail form, authors have proposed a variable die radius design for which they have been able to decrease the maximum twist springback by 46.2%. Owing to the requirements of multi-step forming operations especially for complex shaped parts, Chen et al. [28] have investigated the influence of pre-strain on the twist springback behavior in DP500 steel by forming a P-channel out of DP500 sheets that have been previously pre-strained to 4%. They have observed that pre-straining has resulted in an increase of springback in the formed parts. The authors have explained this behavior as because of the considerable decrease of elastic modulus with applied pre-strain before the forming operation, which has caused in higher springback in the formed part. Lim et al. [29] have investigated whether the time-dependent springback behavior can be observed for various AHSSs such as DP600, DP800, DP980 and TRIP780 steels. The authors have found out that time-dependent springback have been present for AHSS and that its magnitude have increased with the strength level of AHSS. In today’s body in white parts of automobiles, tailor welded blanks (TWB) are frequently used due to the requirements of having high strength and high energy absorption in necessary regions of parts, such as B-pillars. Beres et al. [30] have investigated the springback behavior of tailor welded blanks (TWB) of DP and DCO4 steel sheets by conducting experimental V-bending tests. The authors have observed that springback on the DP side of TWB has been significantly higher as compared to DC04 side. Komgrit et al. [31] have proposed a new U-bending apparatus to eliminate the springback for high strength steels. In their U-bending apparatus, authors have used a slightly hollowed punch and a flat counter punch to impose a counter bending on the sheet. The authors have found out that with the proposed U-bending method, the springback has been able to be decreased to almost zero degrees; however, they have shown that some small imperfections on the bottom could be observed due to counter bending operation. In many studies [33–39], authors have investigated the influence of heat application on the springback behavior for various AHSSs. Pornputsiri and Kanlayasiri [32] have investigated the effect of bending temperature ranging from 25 to 600 °C on the springback behavior of TRIP780 steel. They have found out that springback has been substantially decreased at 400 °C due to decreasing ratio of austenite to martensite transformation during bending. However, the authors have observed a slight increase in the springback at 600 °C as compared to 400 °C. They have concluded that the increased amount of carbide precipitates at 600 °C might have caused the slight increase of springback at 600 °C. Yanagimoto and Oyamada [33] have conducted V-bending tests at elevated temperatures for high strength steels by only heating the bending area of the sheet. The authors have found out a significant reduction in springback conducted at temperatures higher than 750 K. Furthermore, Yanagimoto and Oyamada [34] have conducted another study to explain the reason of reduction of springback at temperatures higher than 750 K for high strength steels and concluded that the reduction of springback has been caused by the increase of creep strains around 750 K. Mori et al. [35] have conducted warm and hot stamping of ultra-high strength steels up to 800 °C by using resistance heating method and investigated the springback behavior. The authors have observed an almost zero springback of the sheet metals at 800 °C. However, they have concluded that the optimum sheet temperature of ultra-high strength steels for effectively reducing the springback has been 600 °C due

Table 1 The chemical composition (wt%) of MART1400 steel

C	Si	Mn	P	S	Al	Nb	Ti
0.143	0.182	1.145	0.0114	0.0140	0.041	0.002	0.033

to higher oxidation problems observed at 800 °C. Lee et al. [36] have applied near infrared rays (NIR) lambs to heat the bending zone of DP980 steel before V-bending operations to reduce the springback. The authors have been able to form the target shape by heating the bending zone above 870 K temperature. Lee et al. [37] later have applied the similar heating method for L-bending operations for DP980 steels and observed that the springback has not been able to be reduced as much as in V-bending operations for the same temperature. The authors have concluded that V-bending and L-bending operations have had a different boundary condition and because of that, higher temperatures should have been applied to reduce the springback for the L-bending operations of DP980 steels. In an earlier study, Nuri ŞEN [38] has conducted V-bending tests of MART1200 steel by locally heating the bending zone with the induction heating method to 300 °C, 400 °C and 500 °C temperatures and observed a significant reduction in the springback at 400 °C temperature.

As given by the above literature, there are only limited number of studies, which consider the springback of MART1400 steels. Therefore, in this study, the influences of bending parameters such as punch tip radius, bending angles, and force holding time on the springback behavior of MART1400 steel have been investigated. FEA play a major role for higher efficiencies in today's sheet metal forming industries. However, in order to benefit from the high prediction accuracy of FEA, rather complex and time consuming kinematic hardening models are used. Hence, in addition to the effect of bending parameters, the prediction ability of different simple isotropic hardening models (Hollomon, Ghosh, Hocket-Sherby, Swift and Voce) on the springback behavior of MART1400 has been investigated. Furthermore, to observe the effect of local heating of the bending area of the MART1400 sheets before the bending experiments, parametric V-bending FEA studies have been conducted at 375 °C and 475 °C temperatures.

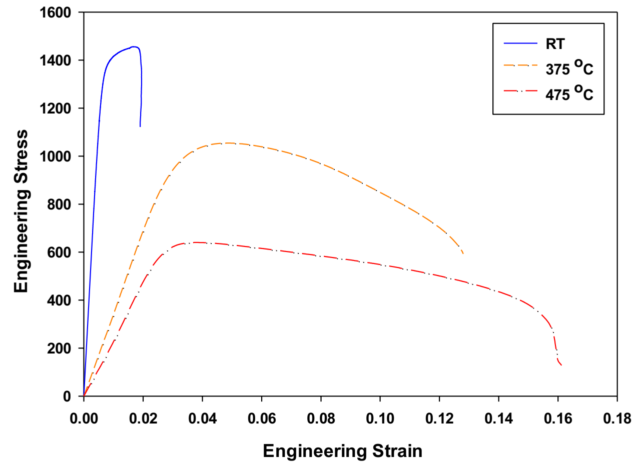

Fig. 1 Engineering stress–strain curves of MART1400 steel at different temperatures and 0.005 s^{-1} strain rate

Table 2 The mechanical properties of MART1400 steel at different temperatures for 0.005 s^{-1} strain rate

Temperature	Yield stress (MPa)	Tensile stress (MPa)	Uniform elongation (%)	Post uniform elongation (%)
RT	1385.5	1455.9	87.89	12.11
375 °C	907.1	1054.6	38.07	61.93
475 °C	601.3	640.1	23.58	76.42

2 Materials and methods

2.1 Material

MART1400 sheet metals, supplied by SSAB, with a thickness of 1.5 mm were used in the V-bending experiments. The chemical composition of the sheet metal was identified by conducting spectral analysis with the GNR Metal Lab Plus spectrometer. The chemical composition of the MART1400 steel is given in Table 1. The mechanical properties of MART1400 steel at room temperature (RT), 375 °C and 475 °C were obtained by conducting uniaxial tensile tests at 0.005 s^{-1} strain rate with Zwick/Roel Z600 tensile testing machine. The engineering stress–strain curves of MART1400 steel are shown in Fig. 1 and the mechanical properties of MART1400 are listed in Table 2.

2.2 V-bending tests

For the V-bending tests, sheet metals were cut to 40 × 40 mm dimensions by guillotine shears. V-bending dies with four different die angles (30°, 60°, 90°, and 120°), punches with different tip radiuses (2, 4, and 6-mm) were manufactured and are shown in Fig. 2. In a previous study, Nuri ŞEN [38] has shown that a considerable amount of springback reduction could be observed by holding the bending force for MART1200 steels. Likewise, Karaagac and Uluer [39] have observed a similar

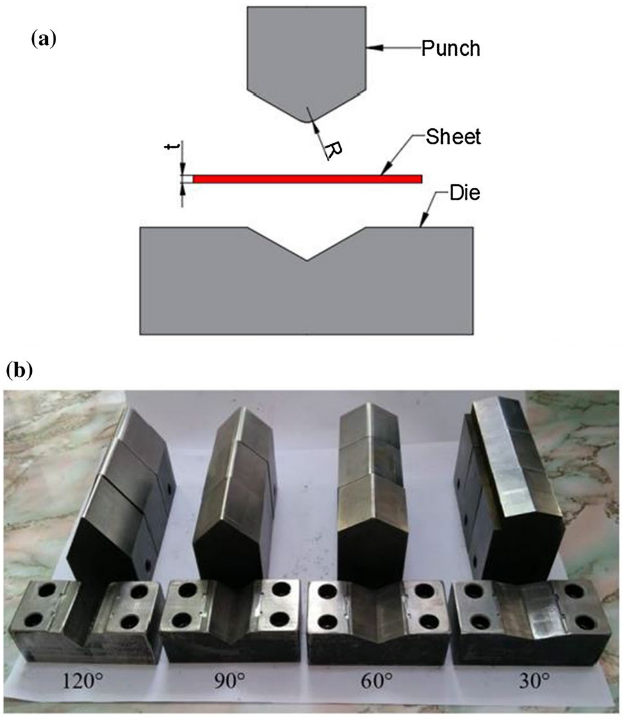

Fig. 2 **a** Experimental setup for the V-bending tests, **b** dies and punches used in the experiments

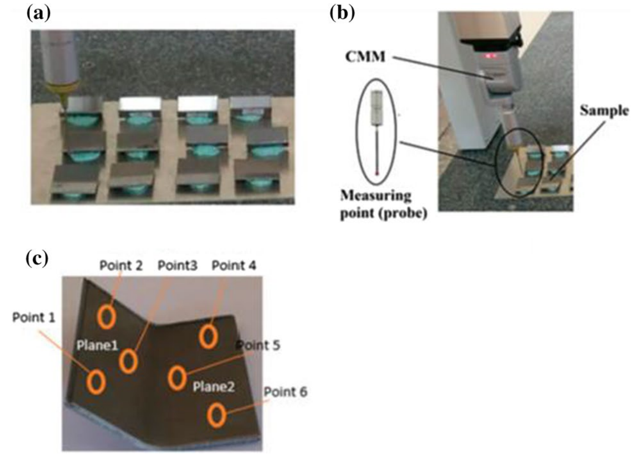

Fig. 3 Springback measurement using CMM. **a** Grounding of sheet samples to the base, **b** creating of contact points on the sheet surfaces, **c** contact points and planes [38]

behavior for DC01 steels. Therefore, to observe the effect of force holding time for MART1400 sheet, V-bending experiments were conducted by holding the punch load on the bent sheets for 0 s and 10 s. Approximately 2 tons of force was used for the punch load in the experiments. The experimental parameters used in the experiments are summarized in Table 3. Springback measurements were conducted by using a Hexagon CMM device. For the measurements, V-bent samples were grounded to the base with a special paste and 3 contact points were created with the CMM probe on each of the two planes of the sheet surface. Angles measured by the CMM device were recorded and the difference between the intended angle and the measured angle were calculated to measure the amount of springback in the sheet metals. The described springback measurement method of the sheets is shown in Fig. 3.

Table 3 The experimental parameters used in the V-bending experiments

Experimental parameters	Levels
Die angle	30°, 60°, 90°, 120°
Punch radius	2 mm, 4 mm, 6 mm
Holding time	0 s, 10 s
Temperature	RT

2.3 Finite element analysis of V-bending tests

In today's manufacturing, FEA is an important necessity for manufacturers to increase their profits by minimizing the error and trials in the development process of their products. Therefore, accurate springback measurements before the die manufacturing process can substantially reduce the costs related to inaccurate die manufacturing and cause expedition of the forming process. However, implementing an appropriate hardening model, which is capable of accurately describing the material behavior, plays an important role in order to obtain accurate prediction results from FEA simulations [40]. Therefore, in this study, different isotropic hardening models (Hollomon, Ghosh, Hocket-Sherby, Swift and Voce) were used in order to describe the material behavior. Isotropic hardening equations and their parameters for MART1400 steel at RT are listed in Table 4. Parameters of the isotropic hardening models were obtained by the curve fitting method. Comparison of the isotropic hardening models with the experimental flow curve between the yield and tensile strength region is shown in Fig. 4. All of the isotropic hardening models were able to well describe the material behavior between yield and tensile strength region of the flow curve despite a small deviation around 1 MPa at the tensile strength point of the experimental flow curve. During plastic deformation operations, quite commonly, larger strains are accumulated on the sheet metals [41]. Therefore, the isotropic hardening models were used to extrapolate the flow curve up to 1 strain. Extrapolated flow curves are shown in Fig. 5. It could be seen that although all the hardening models described the similar behavior between the yield and tensile strength region of the flow curve, different isotropic hardening models predicted different hardening

Table 4 Equations of different isotropic hardening models, their parameters and R^2 values for fitting the experimental flow curve

Isotropic hardening models	Equations	Parameters	R^2
Hollomon	$\tilde{\sigma} = K\varepsilon^n$	$K = 1878.34$ $n = 0.64$	0.995
Ghosh	$\tilde{\sigma} = G_2(\varepsilon + S_2)^{G_3} - G_1$	$G_1 = -0.003$ $G_2 = 1711.62$ $G_3 = 0.031$ $S_2 = 0.0016$	0.999
Hocket-Sherby	$\tilde{\sigma} = \sigma_0 + A(1 - \exp(-b\varepsilon^n))$	$\sigma_0 = 1396.9$ $A = 204.91$ $b = 17.80$ $n = 0.73$	0.997
Swift	$\tilde{\sigma} = A(B + \varepsilon)^n$	$A = 1706.8$ $b = 0.0015$ $n = 0.031$	0.999
Voce	$\tilde{\sigma} = \sigma_0 + V_1[1 - \exp(-V_2\varepsilon)]$	$\sigma_0 = 1396.9$ $V_1 = 90.20$ $V_2 = 244.928$	0.999

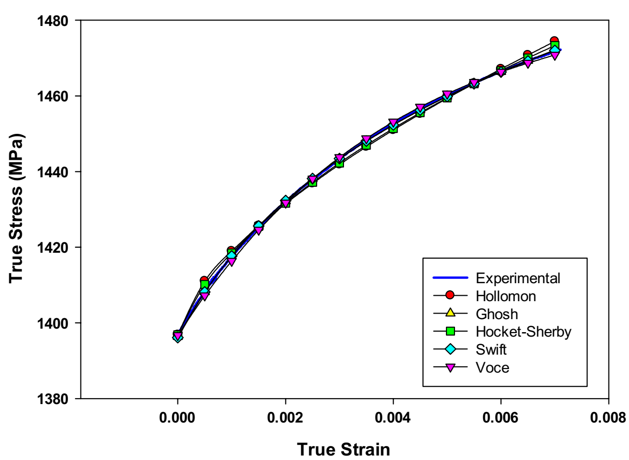

Fig. 4 Comparison of different fitting isotropic hardening models with the experimental flow curve between the yield and tensile stress regions

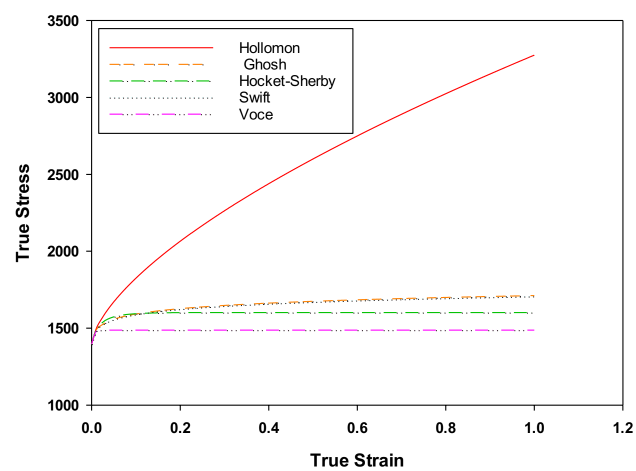

Fig. 5 Extrapolation of flow curve for MART1400 up to 1 strain with different isotropic hardening models

behaviors after tensile strength point on the flow curves. However, Swift and Ghosh isotropic hardening models predicted nearly the same behavior after tensile strength point in the flow curve. Even though Hollomon, Swift and Ghosh were all isotropic hardening models, predicting a continuous hardening throughout the deformation, the stresses predicted by the Hollomon isotropic hardening model were significantly higher. On the other hand, stresses saturated for Voce and Hocket-Sherby isotropic hardening models at 1487 MPa and 1601 MPa, respectively. For the parametric FEA study, only the Hocket-Sherby isotropic hardening model were used to describe the behavior of MART1400 steel at 375 °C and 475 °C temperatures. The parameters of the Hocket-Sherby isotropic hardening model are listed in Table 5 and the extrapolated flow curves up to 1 strain at 375 °C and 475 °C temperatures are shown in Fig. 6.

Table 5 Hocket-Sherby isotropic hardening model parameters and R^2 values at 375 °C and 475 °C temperatures

Isotropic hardening models	Temperature	Parameters	R^2
Hocket-Sherby	375 °C	$\sigma_0 = 1127.2$ $A = 300.56$ $b = 83.07$ $n = 0.99$	0.999
Hocket-Sherby	475 °C	$\sigma_0 = 657.4$ $A = 81.14$ $b = 256.68$ $n = 1.03$	0.999

In this study, Simufact V16 FEA software was used for the springback predictions Die and punch geometries were imported into the Simufact V16 as rigid geometries and the

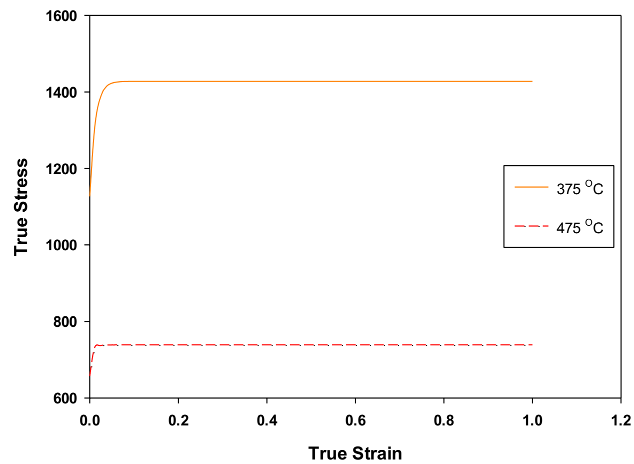

Fig. 6 Extrapolated flow curve with Hocket-Sherby isotropic hardening model at 375 °C and 475 °C

sheets were created as deformable geometries inside the FEA software. The friction coefficient between the contact regions of punch, die and sheet were set as 0.1 Sheetmeshing option was used to mesh the sheets with three layers across the thickness with 0.621 mm mesh size and the total number of meshes on the sheet were 12,288. The springback calculation was conducted with the angle measurement tool available in the FEA software. No force holding time were applied in the FEA. Parametric FEA study was conducted by heating the bending area of the sheets with a 10 mm rod before the bending analysis. The used die, sheet, punch geometries, the springback measurement and the heating methods are shown in Fig. 7.

3 Results and discussions

3.1 The effect of bending process parameters on the springback behavior of MART1400 steels

It is well known that the bending process parameters such as punch tip radius, bending angles, and force holding times have a considerable impact on the degree of springback after plastic deformation [42]. The effects of punch tip radius, die angle and the force holding time on the springback behavior of MART1400 steel are shown in Fig. 8. It can be seen that with the increase of die angle, a significantly higher amount of springback has been observed for MART1400 steel. The increase of die angle results in an increase of deformation around the bending line of the MART1400 sheet. Due to the increase of deformation around the bending line, larger compressive and tensile stresses occur on the opposite sites of the bent sheets, which causes higher unbalanced stresses

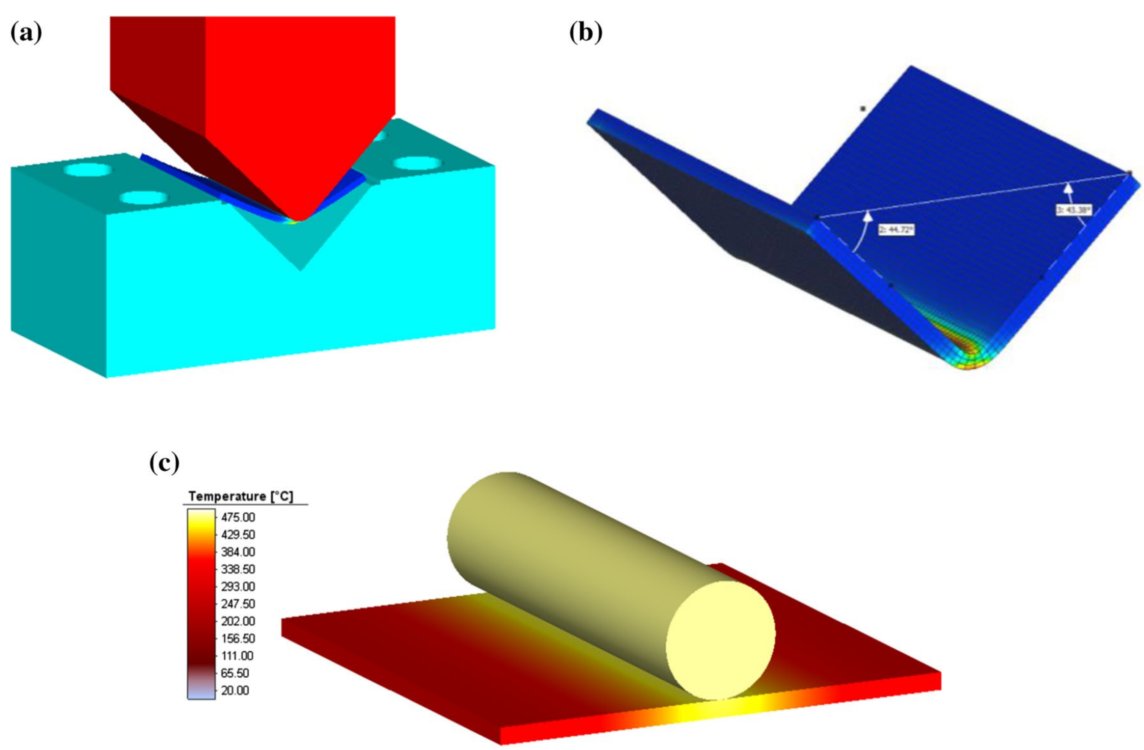

Fig. 7 Finite element analysis model: **a** simulation of bending process, **b** springback measurement method, **c** heating method for the parametric study

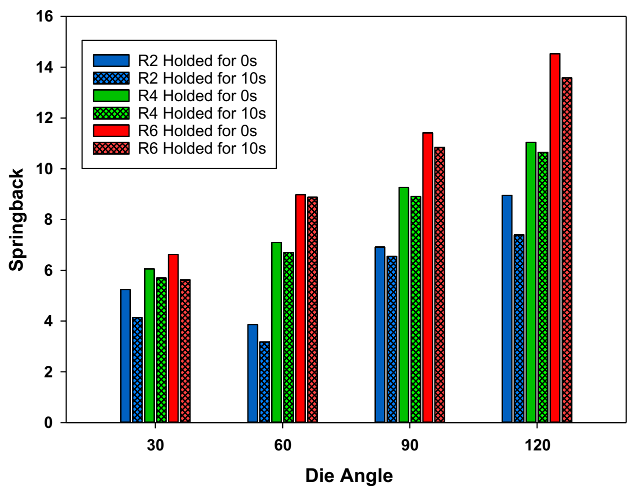

Fig. 8 Springback measurements for different die angles, punch tip radius and holding time at room temperature

and to higher springback angles [43, 44]. Karaagac et al. [44] have also shown in their study that increase of die angles have resulted in larger springback behavior for DP type steels due to increase of stresses around the bending zone. Likewise, Tekiner [20] and ŞEN [38] have observed an increasing springback due to increase of die angle in their study. As could be seen in Fig. 6, a larger punch tip radius has caused higher amount of springback in the sheet metal. It is known that the cause of springback is related to the elastic recovery of the plastically deformed materials and because a larger area of the sheet metal is forced to plastic deformation during the bending operation with a larger punch tip radius as compared to a smaller punch tip radius, the amount of springback has increased with the increase of punch tip radius [45–47]. In addition, a smaller punch tip radius might have caused an arc in between the bending zone and the flat side of the sheet during the bending stage. This arc might have been flattened due to the progression of punch toward the die in the final stages of bending, thus, creating an opposite bending moment in the bent sheets as compared to the bending moments created in the bending zone. Hence, due to the decrease of total bending moment on the sheet, a smaller punch radius can cause a lower springback. Zong et al. [47] have observed that negative springback angles have occurred during the bending of Ti–6Al–4V alloy with a 1 mm punch radius. The authors have explained the formation of negative springback angles by the formation of an arc during the bending and its later flattening in the final stages of bending operation, creating a reverse bending moment relative to the bending moment in the bending zone. Chen and Chiu [48] have also observed a negative springback for the commercially pure titanium alloys for small punch tip radiuses, which the authors have explained to have occurred due to an arc formation during the bending stage. Even though the smaller punch tip radius, R2, haven't caused a negative springback or dropped the springback as near as zero degrees for MART1400 steel, the smaller punch tip radius has caused the smallest springback angles for each bending angles, which indicates that opposite bending moments caused by the arc flattening haven't canceled out the moments in the bending zone, however, has contributed to lower the springback angle. As noted from Fig. 6, the force holding time has had a reducing effect on the springback values of MART1400 steels regardless of bending angle and punch tip radius. Holding the bending force on the bent specimen and thus, restraining the shape for a particular amount of time allows the relaxation of internal stresses [49]. During holding of the force creep strains occur on the sheet which increase the permanent strain in the sheet metal [46]. Lim et al. [29] have shown the presence significant time-dependent springback for AHSS due to creep behavior. Therefore, a considerable amount of springback reduction have been observed for MART1400 steel due to the effect of creep strain by holding the force for 10 s. In an earlier study, ŞEN [38] has also observed a reduction of springback for MART1200 steel by holding the bending force for 10 s.

3.2 Finite element analysis for the prediction of springback and parametric studies

3.2.1 Prediction accuracy of isotropic hardening models of springback in MART1400

Prediction of springback values with a high accuracy before the die manufacturing process can significantly increase the production rates for sheet metal forming industries due to lesser consumption of time during the trial-and-error process. Therefore, it is of high necessary to conduct FEA with the appropriate hardening models for the desired materials and forming conditions. Springback predictions of different isotropic hardening models are shown in Fig. 9. It can be seen that all of the investigated isotropic hardening models have approximately predicted similar springback angles to the experimental values. The average error values of Hollomon, Ghosh, Hocket & Sherby, Swift and Voce isotropic hardening models have been 14%, 8.32%, 8.28%, 9.90% and 10.58%, respectively. Apparently, the high hardening prediction of Hollomon hardening model compared to other isotropic hardening models has resulted in a higher error for the prediction of springback values. Nevertheless, attenuation of similar springback values for different isortropic hardening models indicates that not high strain levels have been created during the bending stage of MART1400 steels since the deviation of predicted stresses for different isotropic hardening models are higher at larger strains. The best prediction has been assessed by the Hocket and Sherby

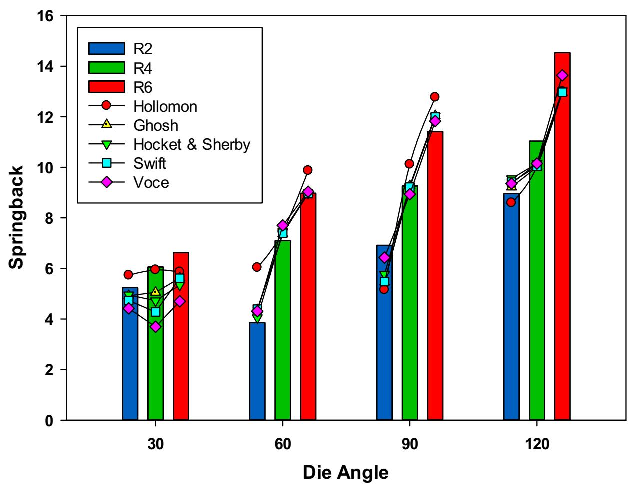

Fig. 9 Comparison of FEA predicted springback values with the experimental springback values

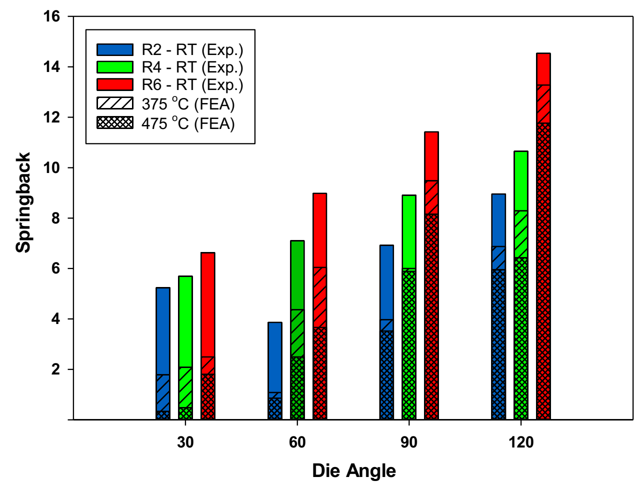

Fig. 10 Springback behavior of MART1400 steel after bending the locally heated sheets at 375 °C and 475 °C

isotropic hardening model with the 8.32% prediction error, which indicates that evolution of stress during deformation for MART1400 has been best approached by Hocket and Sherby isotropic hardening model as compared to other isotropic hardening models. However, it should be noted that the decrease of elastic modulus with the applied strain, which have been found to significantly affect the springback prediction by [25, 26] have been omitted in this study. Therefore, a higher prediction accuracy can be reached by considering the nonlinearity of elastic modulus in further studies.

3.2.2 The effect of local heating around the bending zone on the springback of MART1400

The comparison of the results of springback values of the locally heated MART1400 sheets around the bending area with the experimental values conducted at room temperature is shown in Fig. 10. It can be seen that heat application around the bending area of the MART1400 sheets has resulted in significant reduction of springback values. The average reduction of springback at 375 °C and 475 °C temperatures has been 40.18% and 55.13%, respectively. The main reason of the reduction of springback has been due to the reduction of equivalent stresses around the bending area due to lowering of strain hardening around the bending zone by heating. The equivalent stresses in the bent sheets before the punch removal process are shown in Fig. 11. It can be seen that while at RT, higher stress values have been present in the bending area of the sheet, the stress values have significantly reduced with the increase of temperature. This consequently has resulted in reduction of the unbalanced stress distribution in the bending area and has contributed to lower springback angles. Nuri ŞEN [38] has similarly observed a considerable amount of springback reduction by applying a local heating around the bending zone for MART1200 steel at approximately 400 °C. Pornputsiri and Kanlayasiri [32] have also shown that springback could have been reduced for TRIP780 steels at around 400 °C due to decrease of strain hardening because of lowering of transformation from austenite to martensite during deformation. Likewise, Mori et al. [35] have shown that the springback in ultra-high strength steels could have been significantly reduced at elevated temperatures. However, it should be noted that the softening around the bending zone caused by heat might impact the bendability limit of MART1400 steel. Hence, the impact of heating on the bendability limit of MART1400 steel might be investigated in future studies.

4 Conclusions

In this study, experimental V-bending tests have been conducted for MART1400 AHSS with different die angles, punch tip radiuses and force holding times. Furthermore, FEA has been carried out with different isotropic hardening models and their prediction ability of springback has been discussed. The effect of applying local heating around the bending area has also been investigated with the parametric FEA studies and the following conclusions have been drawn from the study:

- It has been found out that increasing of the bending angle has significantly increased the springback for MART1400 sheets due to the larger stress accumulation in the bending area with the increase of bending angle.
- It has been observed that a larger springback has occurred in MART1400 sheets with the increase of punch tip radius. Observation of lower springback angles

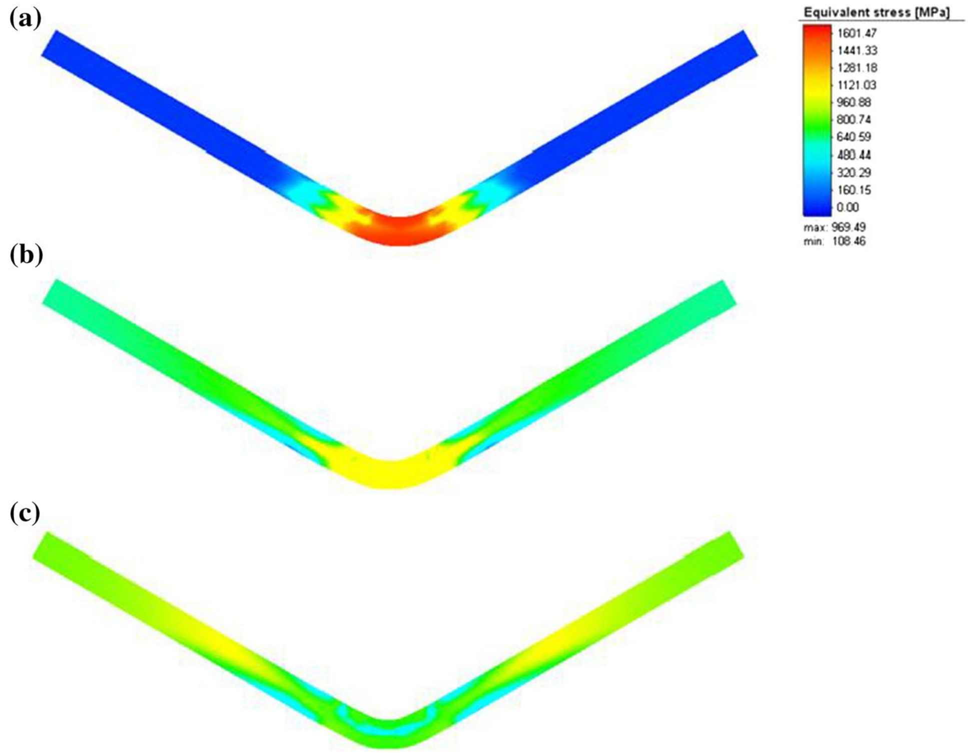

Fig. 11 Equivalent stress distributions along the bent sheets before the punch removal step at **a** RT, **b** 375 °C, **c** 475 °C

for smaller punch tip radius has been related with the decrease of deformation area and the formation of an arc during deformation, which has caused opposite bending moments in the bent sheets and resulted in reduction of springback.

- Holding the bending force of the bent sheets for 10 s has considerably reduced the springback. Creep strains that occur during the force holding time has been considered to be the main reason of springback reduction.
- In the numerical V-bending analysis with different isotropic hardening models (Hollomon, Ghosh, Hocket-Sherby, Swift and Voce), Hocket and Sherby isotropic hardening model has had the best prediction ability with 8.28% average error as compared to Hollomon, Ghosh, Swift and Voce models with 14%, 8.32%, 9.90% and 10.58% average errors, respectively. Thus, it has been found that material behavior of MART1400 could be better represented by Hocket and Sherby model as compared to other isotropic hardening models.
- Applying a local heating around the bending area of MART1400 sheets at 375 °C and 475 °C has resulted in significant reduction of springback in the V-bent sheets. 40.18% and 55.13% reduction of springback has been noted at 375 °C and 475 °C temperatures. The reduction of springback due to heating has been related with the reduction of strain hardening around the bending area, which has caused the reduction of unbalanced bending moments and resulted in lower springback.

5 Future works

It has been found out in this study that the reduction of strain hardening due to heating has caused a lower springback angle for MART1400 steels, however, the impact of heat application at various temperatures on the bendability limit of MART steels might be an another topic of investigation in the future.

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